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TIME DOMAIN MEASUREMENT OF MICROWAVE ABSORBERS

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AIR FORCE AVIONICS LABORATORY
AIR FORCE SYSTEMS COMMAND
WRIGHT-PATTERSON AIR FORCE BASE, OHIO

NOTICES

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OF MICROWAVE ABSORBERS

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FOREWORD

This Final Technical Report covers the work performed under Contract No. F33615-70-C-1722, Project #5546 from 15 June 1970 to 30 September 1971.

The contract with the Sperry Rand Research Center, 100 North Road, Sudbury, Massachusetts, 01776, is to investigate the applicability of time domain measurement techniques to the measurement of complex permittivity (ϵ^*) and permeability (μ^*) of microwave materials.

Dr. A. M. Nicolson, principal investigator, Mr. P. G. Mitchell, Mr. R. M. Mara and Mrs. A. M. Auckenthaler are the Sperry Rand Research Center personnel responsible for this contract.

This report was submitted by the authors; November 1971.

This Technical Report has been reviewed and is approved for publication.

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ABSTRACT

This report describes a prototype time domain metrology system built under contract with the Air Force which could significantly reduce the time required to measure the properties of radar absorbing materials used on aircraft and missiles. During the development of such materials, many measurements are required of dielectric constant and permeability at different microwave frequencies, and by conventional means these can become very tedious. A system has been developed and delivered to the Air Force Avionics Laboratory, WPAFB, which generates subnanosecond risetime pulses, and measures the transient response of samples of the RAM material to these pulses. These time domain responses are measured and recorded on magnetic tape, and a subsequent Fourier transform program yields the desired ϵ^* and μ^* over the frequency range 0.1 GHz to 10 GHz. Actual measurement time averages only about 10 minutes per sample.

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SECTION 1

INTRODUCTION

1.1 RELATIONSHIP TO PREVIOUS WORK

The Interim Report[1] on this contract (AFAL-TR-71-33, February 1971) described in its Sections 2 and 3 the basic principles of time domain measurement of microwave absorbers. To recapitulate, Fig. 1, one diagram from this report, shows a block diagram of the system. In Fig. 1(a) a pulse generator is shown which propagates a subnanosecond risetime pulse through the sampling head of a broadband (dc - 18 GHz) sampling oscilloscope and along a coaxial transmission line to impinge on a small sample of microwave material filling the line. The pulse is partially reflected back to the sampling head, and partially transmitted through the material. The transmitted pulse is subsequently reflected from a short circuit, again passes through the material, and finally reaches the sampling head some time after the reflected pulse. These transient responses are descriptive of the material, and the waveforms are scanned and digitized under the control of a small controller or hardware sequencing system. The digitized waveforms are stored on magnetic tape for processing by a large computer facility, which after fast Fourier transforms and other computation yields the dielectric constant and permeability of the material over a broad frequency range. Figures 1(b) and (c) show how timing markers V_X and V_Y are introduced into the time window to provide stability in measurement of the desired waveforms V_R and V_T . Further details of the procedure are found in the following section. Details of prior work in the area are found in Ref. 2, and a published paper[3] has given typical results for some common materials.

The interim report proposed two alternative hardware systems to carry out these measurements. It was indicated in the conclusion of the report, however, that yet another alternative configuration was being considered; this would use a small programmable digital controller to interact with the various instruments in the system, and accept commands from the person operating the system. The advantages stressed were of low cost, and

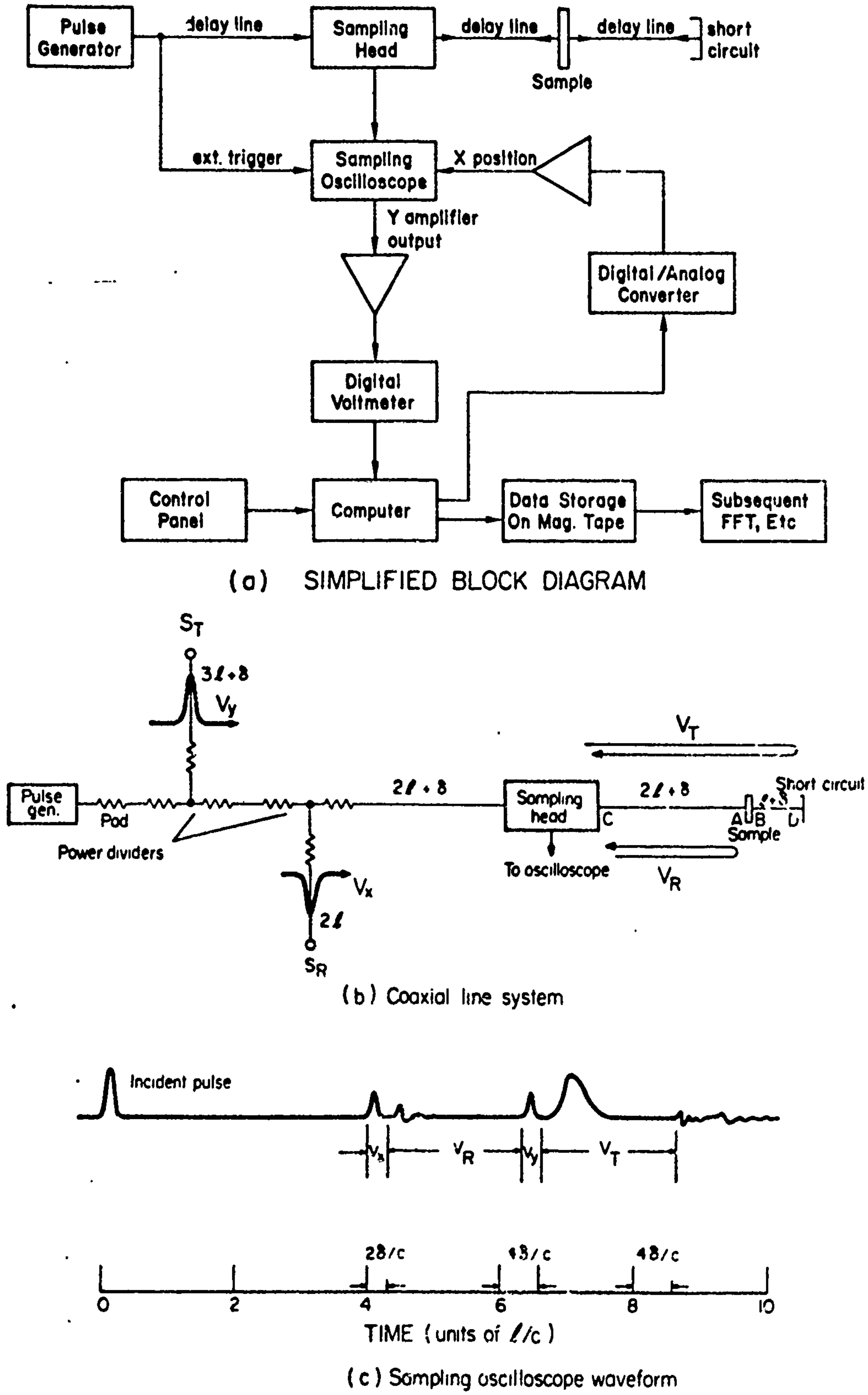


FIG. 1 Practical system with two reference ramps.

the flexibility which allowed changes in the sequence of operations readily to be made. After further discussions with AFAL, this controller-operated system was decided upon, designed, tested and delivered to the Air Force within seven months. This report describes the operation and design of the Time Domain Metrology System, employing a General Automation SPC-12 programmable digital controller.

1.2 BRIEF DESCRIPTION OF EQUIPMENT

The equipment measures the complex permeability and permittivity of materials over the frequency range 0.1 to 10 GHz; it is shown in Fig. 2. In the center of the picture may be seen the pulse generator box (compare with Fig. 1(a)), which also contains delay lines and has the oscilloscope sampling head and dielectric sample holder mounted on top, as is described in Section 3.1. It is connected to the sampling oscilloscope at the bottom of the instrument rack; the rack also contains a digital voltmeter, the SPC-12 controller, and the operator control panel. Below the rack is an ASR33 teletype, which is only used to load programs to the controller. To the left of the instrument rack, another rack contains a display oscilloscope to show collected waveforms, and the tape recorder on which collected data is written prior to processing. To the right of the picture is the high temperature oven, with its controller above. This is used with a special Kovar high temperature sample holder, as described in Section 6.

The instrument rack is seen in more detail in Fig. 3. Below the SPC-12 controller is the interface unit, containing all the hardware necessary to couple the SPC-12 to the other instruments; a description of this is given in Section 3.2. The control panel is the means by which the operator is directed to carry out each step of the measurement sequence, and indicate when he has completed a required action. Each step is indicated by a lighted push button; when the operation has been performed (such as changing a dielectric sample), the operator pushes that button, and the sequence proceeds. The operator sequence is described in detail in Section 2, which forms the operator's manual for the equipment. An outline of the program written for the SPC-12 and stored in its memory is given in Section 4, and the Fortran

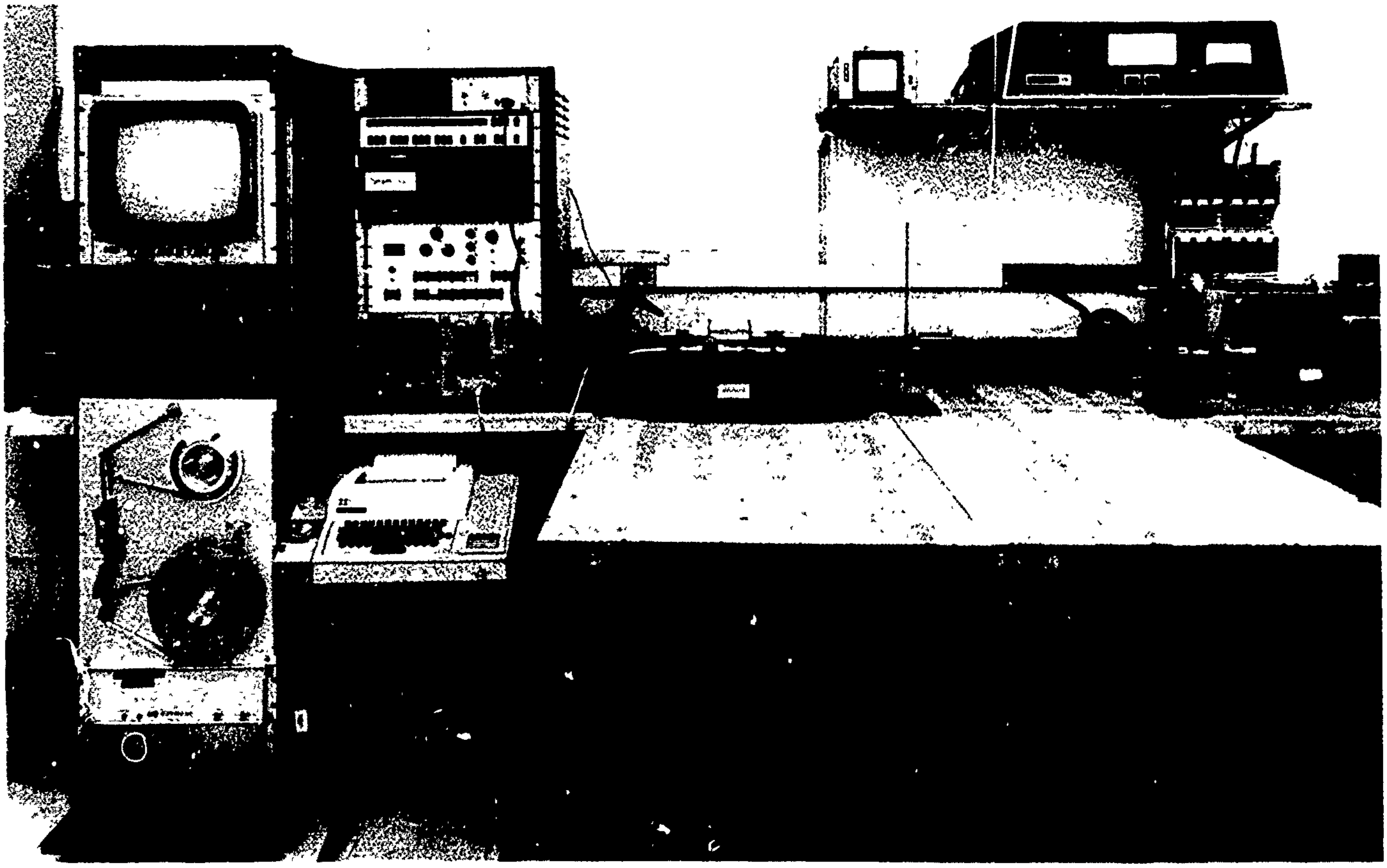


FIG. 2 Complete time domain metrology system.

FIG. 3 Instrument rack.

program which processes the magnetic tape data is described in Section 5. Methods for high temperature measurements are discussed in Section 6, and results obtained on the measurement of μ^* and ϵ^* for many materials are given in Section 7. Finally, recommendations for further work are given in Section 8.

This report was prepared by Dr. A. M. Nicolson and Mr. P. G. Mitchell of Sperry Rand Research Center. Mr. R. M. Mara was responsible for development and construction of the interfacing equipment and the pulse generator unit, and Mrs. A. M. Auckenthaler for writing the original Fortran program.

SECTION 2

OPERATING INSTRUCTIONS

2.1 INTRODUCTION

This section comprises an OPERATORS MANUAL. It contains a description of the equipment, the measurement program, the operating sequence, and details of handling the Fortran and SPC-12 programs. With addition of the high temperature materials in Sect. 6, this is a complete compilation of the information needed to operate the Time Domain Measurement System..

The equipment samples, digitizes and stores subnanosecond risetime waveforms in the time domain that can subsequently be used to yield frequency domain information by Fourier transform. Each waveform is measured over either of two time windows on a Hewlett-Packard Model 141B/1430B sampling oscilloscope. The oscilloscope output is digitized by a Hewlett Packard Model 3480B digital voltmeter, and written on magnetic tape with a Digi Data Model 1557-200 recorder. The measurement program is under the control of a General Automation SPC-12 digital controller.

A simple schematic of the system is shown in Fig. 4(a). The pulse generator produces a 100 psec wide pulse, which propagates past two shunt stubs, through the sampling oscilloscope head, and through the dielectric sample, eventually to reflect at a short circuit. The wave reflected from the dielectric sample returns to the sampling head within the R window, as shown in Fig. 4(b). The wave reflected from the short circuit propagates back through the dielectric sample again, arriving at the sampling head during the T window. Subsequent multiple reflections form residues which occur beyond the end of the T window. The two stubs have lengths chosen which provide spikes just prior to the R and T windows, and these unchanging spikes are used by the controller to reference the two time windows; as different materials are placed within the sample holder, different waveforms will appear within the R and T windows.

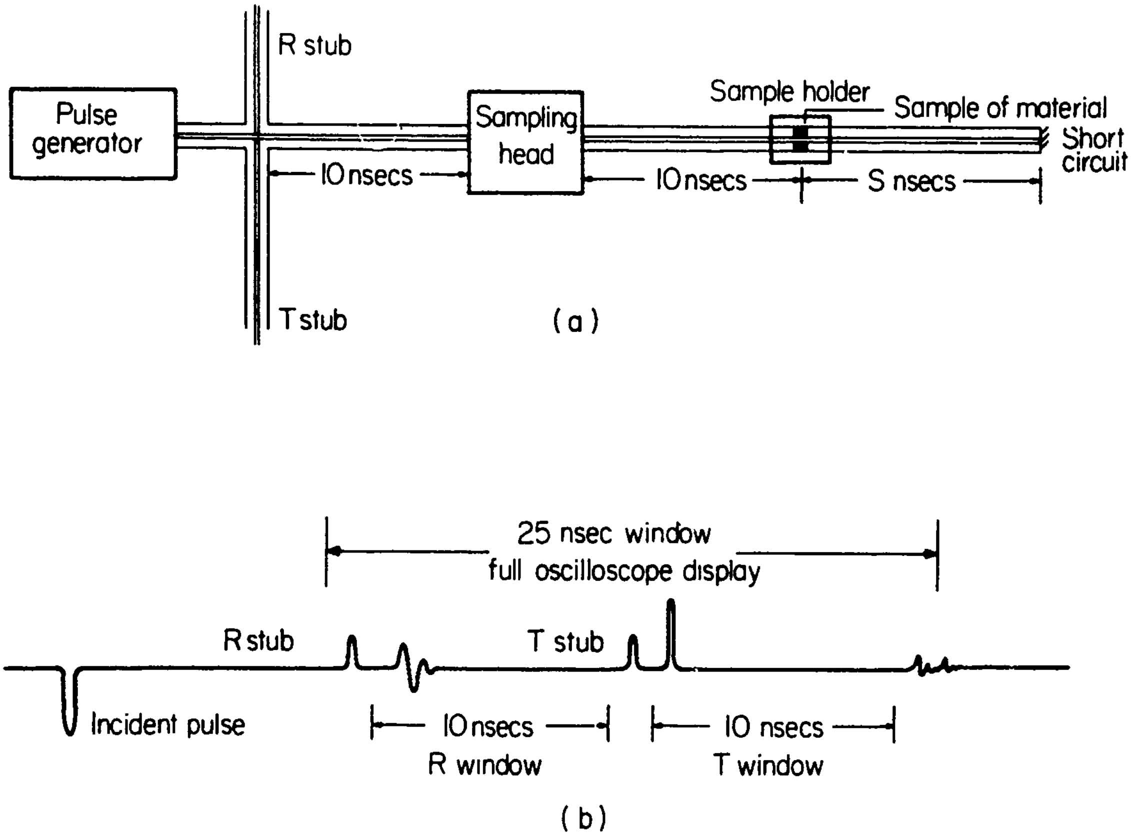


FIG. 4 (a) Schematic of time domain analyzer.
(b) Waveform at oscilloscope sampling head, with dielectric material in sample holder.

The system scans the R and T windows in a certain sequence for the purpose of materials measurements, namely in the order R, R, T, T, (R, T), with repeats of (R, T). The normal sequence is

(1) R window: metal slug in sample holder, gives incident waveform for R window. See Fig. 5.

(2) R window: no material in holder, gives background for R window. See Fig. 5.

(3) T window: no material in holder, gives incident waveform for T window. See Fig. 5.

(4) T window: 50 Ω termination on further end of sample holder, gives background for T window. See Fig. 5.

(5) R window: dielectric sample #1 in holder, gives R waveform. See Fig. 5.

(6) T window: dielectric sample #1 in holder, gives T waveform. See Fig. 5.

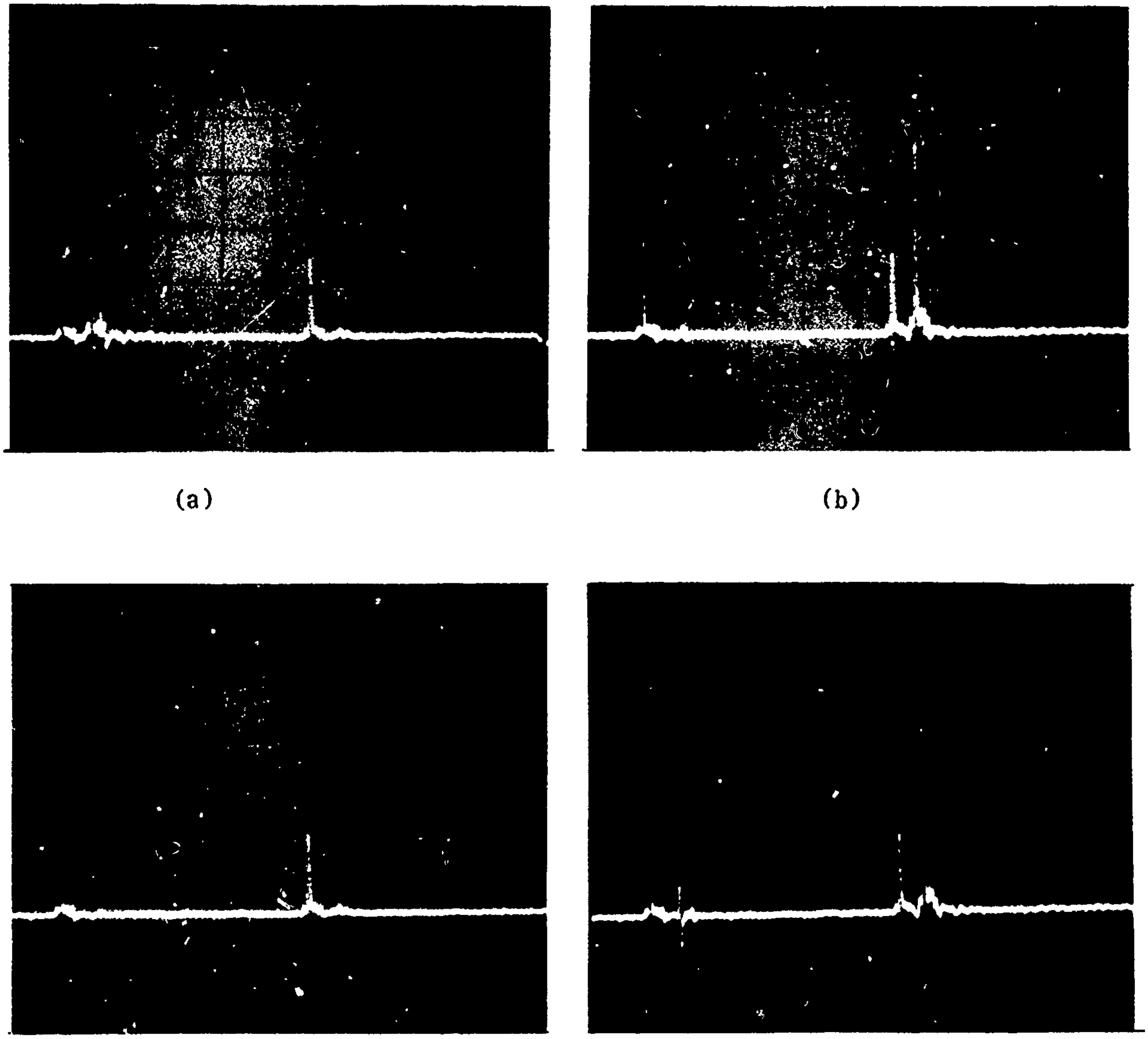
(7) R window: continue as in (5) with dielectric sample #2 in holder ... etc.

Although intended for materials measurements, certain networks could also be measured by substituting them for the sample holder. When only the R or T window alone is of interest, the capability is available to measure repeatedly over that window alone. When the first four measurements (1) to (4) above have once been taken, it is possible to restart a measurement sequence at step (5) above if desired.

When the above sequence of waveforms has been digitized and recorded on magnetic tape, the data is processed by a Fortran program on a remote computer, to yield a printout giving the complex permeability and permittivity of the material as a function of frequency. The program requires as input, in addition to the data, the sample thickness (in mils), the scan width for each waveform (typically 2.5 nsec or 10 nsec), and the number of data points on each waveform (typically 256 or 1024).

2.2 INSTALLATION

Power to the equipment passes through a distribution box in the rear of the rack, and is under the control of a single switch. Individual switches are located on each piece of equipment. The pulse generator also



(a) (b)

(c) (d)

Horiz. scale: 2.5 nsec/div.
Vert. scale: 100 mV/div.

FIG. 5 Typical oscilloscope waveforms.

(a) Metal slug in sample holder (b) Empty sample holder
(c) 50 Ω termination on sample holder (d) With dielectric sample

has a battery source of power controlled by a switch on the top of the box and interlocked to the AC line switch on the side of the box. The battery is sufficiently large that the current drain of 7 mA will be negligible, and the battery life can be expected to be its shelf life of about 2 years. The tape recorder which is in a separate rack, and an auxiliary oscilloscope, which may be used to monitor the waveform data, are not powered through the distribution box. The oven and controller require separate single phase 208V power. A single common ground should be provided for the equipment. The SPC-12 controller should be plugged into the end socket on the distribution box. A pushbutton next to this socket will allow momentary interruption of power to this socket to reset the controller.

Interconnection between equipment is summarized below:

FROM	TO	CONNECTION
I/O box	SPC-12	Multiple wire cable
SPC-12	I/O box	Multiple wire cable
I/O box	DIGITAL VOLTMETER	Multiple wire cable
I/O box	TAPE RECORDER	Multiple wire cable
SAMPLER HEAD	SAMPLING OSCILLOSCOPE	Multiple wire cable
TELETYPE	SPC-12	Multiple wire cable
PULSE GENERATOR TRIGGER OUT	PULSE GENERATOR TRIGGER INPUT	Coaxial cable
CONTROL PANEL SCOPE Y	SAMPLING OSCILLOSCOPE Y OUTPUT	Coaxial cable
CONTROL PANEL TO DVM	DIGITAL VOLTMETER LO (gnd) HI (signal)	Coaxial cable
CONTROL PANEL SCAN INPUT	SAMPLING OSCILLOSCOPE SCANNING EXT. INPUT	Coaxial cable
REAR PANEL R2	AUXILIARY OSCILLOSCOPE EXT. X (horizontal)	Coaxial cable
REAR PANEL R3	AUXILIARY OSCILLOSCOPE NORMAL Y (vertical)	Coaxial cable

The SPC-12 controller has a key lock at the rear, which should remain in the locked (upright) position except when programs are being entered from the teletype. The effect of the lock is to prohibit entries

from the switches on the front of the controller, which could damage the program in memory. If it is desired to change, or re-enter the program from paper tape, the procedures are given under Sect. 7.

The scan of the sampling oscilloscope is under the control of the SPC-12. The location in time at which the waveform is being measured is determined by the DAC register R3, and jitter is compensated by locking to the timing stub by DAC register R2.

The output of the sampling oscilloscope is digitized by the digital voltmeter, and stored as data in the SPC-12. The calibration of the sampling oscilloscope output should be approximately 512 mV/cm. A good procedure for adjusting the oscilloscope output is

(1) Establish a long SCAN by dialing 1024 POINTS/SCAN and 16 SCAN REPEATS, and pushing the buttons in sequence until a red SCAN light is lit. The settings of the other knobs and switches are of no consequence.

(2) Set the oscilloscope trigger to FREE RUN, to obtain a horizontal sweep on the oscilloscope.

(3) Set the vertical height of the trace to be across the centerline of the graticule. Adjust the DC LEVEL of the Y OUTPUT with a small screwdriver, until the digital voltmeter reads approximately zero.

(4) Move the oscilloscope trace up 1 cm. Adjust the AMPLITUDE until the meter reads approximately -512 mV. The Y OUTPUT of the oscilloscope will now be appropriately scaled. The calibration can be verified by other settings of the oscilloscope trace.

(5) Push ABORT and COMPLETE to return to READY. Be sure a tape is not loaded when COMPLETE is pushed because an EOF command is given.

The sampled data is time averaged by an integrator on the control panel. The oscilloscope also has an optional smoothing system of its own, which has little or no effect on the results because of this integrator. It is necessary to adjust the RESPONSE as described in the Hewlett-Packard 1411A plug-in manual to ensure the sampling loop gain in near unity. The oscilloscope should be operated on NORMAL, without smoothing.

The tape recorder should not be loaded with tape and brought to BOT until data is ready to be taken. An EOF is needed to head the data, and this must be entered by pushing the button on the tape recorder once. When the COMPLETE button is pushed an EOF is written, even when no data is being recorded; so care should be taken not push COMPLETE until the measurement program is complete. Turning power off and on or resetting the SPC-12 also generates an EOF, so care should be taken not to spoil data on a tape in this way.

2.3 MEASUREMENT PROGRAM

The SPC-12 that controls the measurement program has 4096 8-bit words of memory. Half of the memory contains a program to direct sequencing and collect data, and the other half to store the data before it is written on tape. The program does the following:

(1) Directs the sequence of the measurement by input from push buttons and switches and output to lights and relays.

(2) Directs the waveform scan by output of voltages to the sampling oscilloscope through D/A converters and amplifiers and inputs voltages from an amplifier and through the digital voltmeter.

(3) Compiles and does preliminary arithmetic on the waveform data.

(4) Controls long-term timing jitter to be less than 1 psec by locking the measurement of each time window to a reference marker that precedes each window.

(5) Makes the scan results available for display on an auxiliary oscilloscope.

(6) Controls the tape recorder in writing the data.

The control panel is the interface by which the operator may direct and observe the progress of the measurement. The buttons light in order of the program sequence, guiding the operator in setting up the experimental conditions required by each step of the measurement.

YELLOW and GREEN buttons instruct the operator what is to be his next action. He should push the lighted button after he has set up the conditions required for that part of the measurement.

RED lights indicate that a scan is in progress.

The WRITE/NOT WRITE condition commutes on pressing the button. Data is stored in memory and available for display after each scan. It is written immediately before the next scan, after the button for the next operation has been pushed. The system is prevented from writing the same data more than once in the event of an ABORT.

ABORT has two possible uses: During the yellow light sequence (steps B2 to B5 below), pushing ABORT causes the program to return to READY, allowing all parameters to be reset. During the green-red sequence (steps B6 to B12 below), pushing ABORT during a red light (i.e., a waveform is currently being scanned) causes a return to the same green light, allowing that scan to be repeated when its button is pushed. During a green light (a scan has been completed but not recorded) the program returns to the preceding green light, allowing the scan to be repeated. ABORT is ineffective while data is being written on magnetic tape.

TAPE lights either for broken tape or an end-of-tape marker. If TAPE is lit while data is being written, the data on the tape will have been lost. The program will stop and return to READY when the fault is corrected or when ABORT is pushed.

A SAMPLE entry option has been incorporated that allows use of the previous reference waveforms with a new CODE. This should prove useful in the high temperature measurements, when the time to heat up and cool down the sample holder is long. The equipment may be turned off in the meantime. SAMPLE entry is allowed only if the previous set of reference measurements was completed.

When COMPLETE is pushed, data and an end of file is written, and the program returns to READY. When a tape has been mounted and brought to BOT, care should be taken not to push COMPLETE before the measurement program is ended, because the EOF is written. COMPLETE may be pushed at any GREEN light, but to have correct data format it should not be pushed except when lit.

2.4 OPERATING SEQUENCE

The normal program of measurement will follow the sequence described starting with step B1. The starting points of the R and T scans should remain

correct from the previous run, so it should normally be possible to proceed directly into the measurement with only a small trim to points P2 as described in Step B5.

However, if it is desired to adjust the reference points or confirm that the scan is starting at the right time in each of the two windows, the following procedure in A1 through A6 is recommended.

A1 Mount a sample and observe the oscilloscope display as in Fig. 5. The sample should remain in the line throughout this procedure.

A2 Do steps B1 to B5 below.

A3 Leave NOT WRITE lit, and do not mount the tape.

A4 Push SHORT and scan the R window. Observe that the display on the oscilloscope shows the first peak at 0.4 nsec after the beginning of the scan. If it does not, push COMPLETE and repeat the procedure, making an adjustment to P3R.

A5 When the R window is satisfactory, continue the sequence to COAX (T) and observe that the peak also lies at 0.4 nsec after the beginning of the scan. If it does not, push COMPLETE and repeat the procedure, making an adjustment to P3T.

A6 When scanning 1024 points, care should be taken to ensure the T measurement does not include the second-time-around residue that occurs immediately after the end of this window, which could introduce an error if it were included in the data.

The normal program of measurement is as follows:

B1 POWER ON initiates the program and lights READY. The oscilloscope should be set up to give a display as in Fig. 5, on NORMAL scanning, and with MILLIVOLTS/CM set to 100. The actual time calibration is set to 2.5 nsec/cm by adjusting MARKER POSITION and VERNIER on the oscilloscope until the R stub spike is exactly on the graticule line 1 cm from the left hand edge, and the T stub spike is exactly at 5.6 cm from the left hand edge. Then switch the oscilloscope to EXTERNAL scanning.

To proceed, push READY.

B2 CODE is lit.

Set the sample code number on the thumbwheel switch. This code will be written with each block of data.

To continue, push CODE.

B3 SCAN POINTS (and sometimes SAMPLE (R))is lit.

Each of the two time windows has a maximum width of 10 nsec, which is divided into 1024 discrete positions. A unit INCREMENT is thus approximately 10 psec; with INCREMENT = 1, the time interval between points (the Nyquist interval) is 9.766 psec; with INCREMENT = 2, the Nyquist interval is 19.53 psec, and so on. The number of points in each scan may be 64, 128, 256, 512 or 1024, but the product POINTS/SCAN X INCREMENTS $\leq$ 1024. The program checks that this condition is satisfied, and will not advance if it is not so.

If SAMPLE (R) is lit, an entry into the program at this point is possible, and discussed in Sect. 2.5.4.

To continue, push SCAN POINTS.

B4 SET 0, 10, 25 is lit.

3 spots will be displayed on the screen. Set these to be at 0 cm, 4 cm, and 10 cm using the SET 0 NS, SET 10 NS, and SET 25 NS potentiometers on the control panel, respectively (see Fig. 6(a)).

To continue, push SET 0, 10, 25 NS.

B5 POSITIONS REFS is lit.

6 spots will appear on the oscilloscope screen, 3 describing the R window and 3 the T window. The points may be moved by setting the REFERENCE SELECT switch and holding the SLEW switch to the left or to the right. There is a FAST and a SLOW slew speed.

The points should be positioned as shown in Fig. 6(b).

P1R moves points 1 and 2 together. Position point 1 on a flat portion of the waveform close to the beginning of the reference marker, such that small timing shifts will not affect its vertical position.

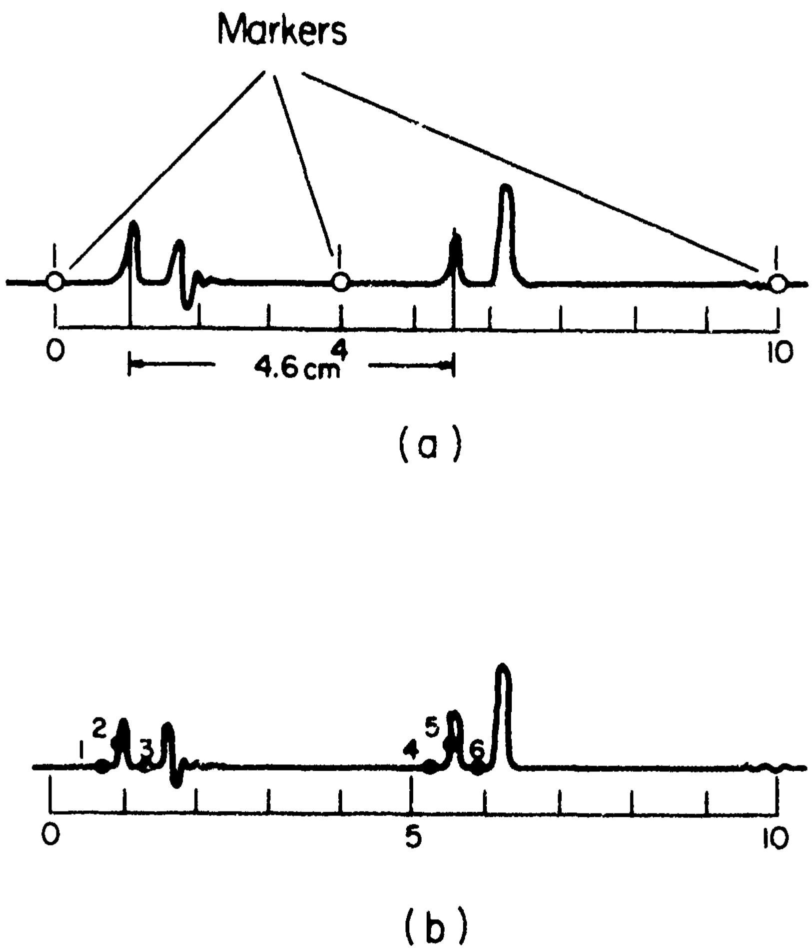


FIG. 6 Setting markers: (a) 0, 10 and 25 ns, (b) reference points.

P2R moves point 2 alone, and more slowly. Set point 2 about halfway up the <u>rising</u> edge of the R marker. Timing jitter will cause relatively large changes in the vertical position of this point and this information is used to provide time stability. During the scanning routine, the voltage at this point is repeatedly compared against its initial value, and this controls the time stabilization.

P3R moves point 3 alone, which is the scan point at its starting position. With a dielectric sample in the holder, ideally P3R should be set to be 0.4 nsec (0.16 cm) before the first peak of the R window response.

The T window points should be positioned similarly. With a dielectric sample in the holder, ideally P3T should be 0.4 nsec before the peak of the T window response.

To continue, push POSITION REFS.

B6 SHORT and NOT WRITE are lit.

Pushing NOT WRITE will light WRITE and enable data to be written. This switch may be pushed at any time, changing from NOT WRITE to WRITE and vice versa. Everything is now prepared to begin recording data. Mount the tape in the recorder and bring to BOT, then give a single EOF.

The metal short should now be placed across the coaxial line in the sample holder, and positioned with the gauge block at 1 inch from the incident connector (i.e., the connector nearer the sampling head). The end-line, connected to the other sample holder connector, should be terminated in a short, which will normally remain in position throughout the run.

To continue, push SHORT.

SHORT RFFL (red) will be lit during the scan.

B7 COAX (R) is lit.

The short should be removed and replaced by a continuous section of center line in the sampler holder.

To continue, push COAX(R).

Data from SHORT will first be written if WRITE (red) is lit, and then COAX REFL (red) will be lit during the scan.

B8 COAX (T) is lit.

No change is made to the sample holder, i.e., the continuous line remains in the sample holder.

To continue, push COAX(T).

Data from COAX(R) will first be written if WRITE (red) is lit, and then COAX TRANS (red) will be lit during the scan.

B9 50 Ω is lit.

The end line should be removed from the sample holder and replaced by a 50 Ω termination. (An exception to this is when a high temperature measurement is being made, in which case it may be easier to terminate the line in 50 Ω - see later discussion on high temperature measurements.)

To continue, push 50 Ω .

Data from COAX(T) will first be written if WRITE (red) is lit, and then 50 Ω TRANS (red) will be lit during the scan.

B10 SAMPLE (R) is lit.

The sample should be placed in the sample holder with its first face positioned with the gauge block at 1 inch from the incident connector. The end line is reconnected, with a short circuit at its far end.

To continue, push SAMPLE (R).

Data from either 50 Ω or SAMPLE (T) (whichever run preceded) will be written if WRITE (red) is lit, and SAMPLE REFL (red) will be lit during the scan.

B11 SAMPLE (T) is lit.

No change is made - the sample should remain in the sample holder, and the line continues to be terminated in a short.

To continue, push SAMPLE (T).

Data from SAMPLE(R) will first be written if WRITE (red) is lit, and then SAMPLE TRANS (red) will be lit during the scan.

B12 SAMPLE(R) and COMPLETE are lit.

The sample may now be changed, or repeat data taken of the existing sample, or the measurement completed.

To continue sample measurements, change samples if required, and then push SAMPLE(R). The program will continue as described in step B10.

Alternatively, to conclude the measurement, push COMPLETE. Data from SAMPLE(T) will be written if WRITE (red) is lit, an end of file will be written, and the program will return to READY.

2.5 ADDITIONAL FEATURES

2.5.1 Auxiliary Oscilloscope Display

When scanning is complete, the red light goes out, and the program waits at the next green light for confirmation to continue. During this wait, a display of the scan may be observed on an auxiliary oscilloscope with conventional X-Y output. X and Y are supplied from BNC sockets labeled R2 and R3 respectively at the rear of the instrument rack. If the data is acceptable, pushing the green button will cause it to be written on tape (provided WRITE is lit), and the next scan will begin. If the data is not acceptable, then pushing ABORT will cause the previous green light to come on and allow a repeat of that scan.

R2, the oscilloscope X position, also has significance during the scan. It measures the amount of correction voltage that is currently contained in the timing correction. The nominal position is with R2 at half full scale, or X centered on the oscilloscope. As timing drifts occur, they are tracked and compensated by R2, which shows as a shift of the spots on the oscilloscope screen to the right or left of center. If it is observed that R2 is moving towards either edge of the display, there is a danger it may go outside its dynamic range. Should this situation occur, slowly and carefully adjust the MARKER POSITION potentiometer on the sampling oscilloscope to make an analog correction that will bring the spots back to the center. After moving the

waveform, it may be advisable to repeat that scan by means of the ABORT button, which may be pushed at any time. This technique may be useful when taking advantage of the SAMPLE restart after the equipment has been turned off (see Sect. 2.5.4).

2.5.2 Repeat of the Four Reference Waveforms

Although it is not explicitly offered by the control display, a third alternative is available when, at the end of the SAMPLE(T) measurement, the SAMPLE(R) and COMPLETE lamps are lit. This is to repeat the four reference waveforms, and is carried out by inserting the short circuit in the sample holder, and pressing the SHORT button. The program resumes from step B6. This was incorporated while the equipment was being developed to permit a comparison of each of the reference waveforms at the beginning and end of measurements; significant differences indicate uncompensated timing shifts, or changes in waveshape due, for example, to varying connector mismatch. Use of this feature requires an addition to the main FORTRAN program.

2.5.3 Measurements over a Single Time Window

The system has been designed primarily to make a sequence of scans over the R and T windows which goes: R, R, T, T, (R, T) with repeats of the (R, T). In other applications, however, it may be required that only a repeated series of measurements over the same time window is required, as when, for example, measuring the reflection coefficient of a RAM sample backed by a short circuit. The program accommodates this requirement as follows:

Carry out the normal set-up procedure, steps B1 to B5, setting the R window P_{1R}, P_{2R} and P_{3R} parameters for the desired single time window. The P_{1T}, P_{2T}, and P_{3T} positions are irrelevant. When the first window is prepared, push SHORT; this scans the R window, ending when COAX(R) is lit. Push SHORT again when ready, and repeat step B6. The SHORT button may be repeatedly pressed for an indefinite number of scans of the R window.

2.5.4 Restarting with Same Reference Waveforms

It is preferable to retake the four reference waveforms at the outset of measurements. However, it is possible to continue measurements with the same

reference waveforms after the equipment has been shut down and then switched on again, provided the oscilloscope settings are not altered and the full four waveforms were previously acquired. Then after the CODE button is pushed on restarting, the option is offered by the lights at step B3 to branch immediately into the first SAMPLE(R) scan. Succeeding waveforms will be referenced to previously acquired reference waveforms, the time position locking scheme ensuring synchronism.

If the SCAN POINTS button is pushed, however, this capability is voided until a new complete set of reference waveforms has been acquired.

It is worth noting that the controller does not consider a waveform to have been fully acquired until the next green button or COMPLETE has been pushed. This scheme allows a waveform to be discarded with the ABORT button and the scan repeated before it is written on tape. For example, the 50 Ω reference waveform is considered to have been acquired only after either SAMPLE (R) or COMPLETE has been pushed in confirmation of the data.

2.6 DATA INPUT FOR FORTRAN PROGRAM

A program written in Fortran is used to process the magnetic tape. It requires two input parameters on data cards, and these guide the sequence of operations of the program in the manner indicated by the flow chart in Fig. 7. The integer NFOR is nominally the number of data points in each record (i.e., 64, 128, 256, 512 or 1024). It has a special significance if read as a zero or a negative number, in that it causes the program to halt. The floating point number THIK is nominally the sample thickness in mils (thousandths of an inch), and is read after the program has input the four reference waveforms. Two further waveforms are read for the sample reflection and transmission, and the results are μ^* and ϵ^* printed out. A new THIK card is then read prior to the next pair of sample waveforms. However, if THIK is read as zero, the program instead assumes that the next four waveforms are the reference waveforms repeated, and it reads these and prints out differences between corresponding points on each waveform. The program then reads another NFOR card. If THIK was read as a negative number (such as -1.0), the NFOR

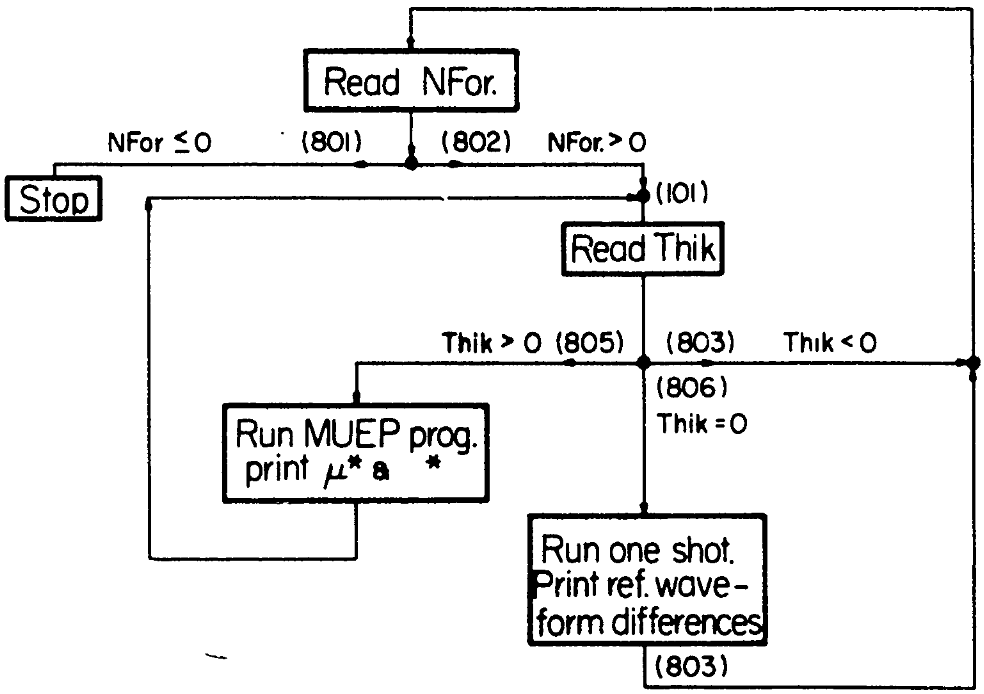


FIG. 7 Flow diagram for data card sequence.

card is immediately read. If NFOR is greater than zero, the first four waveforms on a new file are read. The flow chart of Fig. 7 indicates this sequence of operations.

2.7 PAPER TAPE HANDLING FOR SPC-12 DIGITAL CONTROLLER

2.7.1 Introduction

The SPC-12 controller has a magnetic core memory, the contents of which are not lost when power is off. The program is stored in the lower 2048 memory words, and collected data in the upper 2048 words. The program is automatically begun when power is switched on, and under normal conditions it need never be re-entered into memory. It is protected against alteration by the SPC-12 control switches by a lock-switch found on the rear panel of the controller, which is normally in the LOCKED condition. The procedures which follow are thus not part of the normal measurement routine, but are included for the special cases where

(1) the stored program has somehow become damaged; or

(2) when it is desired to modify the program.

Some familiarity with the SPC-12 Programming Manual would be helpful for the discussion which follows. Two punched paper tapes have been supplied for use with the Time Domain Analyzer. The first is the measurement PROGRAM TAPE, which fills the lower half of memory. The second is a special version of the SPC-12 BUS II operating system, in which the TTY I/O, LOADER, PUNCHER, and MODE CONTROL routines have all been relocated into the upper part of memory. The loading procedure has the following steps (full details given later):

(1) Ensure the BOOTSTRAP program is available at locations 1000/1051. If it is not there, it must be loaded on the SPC-12 switches. Then it is set running.

(2) The BUS II tape is placed in the tape reader, and the short BOOTSTRAP program loads the LOADER proper into locations 264/476, and transfers control to this loader. This loader then continues to load BUS II from the same paper tape into the part of the upper half of memory. It also puts another version

of the loader in the upper half of memory. When the BUS II tape has been loaded, pressing the RESET button on the rear of the equipment rack causes control to be transferred to the BUS II program.

(3) The PROGRAM TAPE is placed in the tape reader and loaded into the lower half of memory by the new BUS II loader. Finally, pushing the RESET button again causes control to be passed to the measurement program, and the READY light is lit.

The upper half of memory is reserved for data during a measurement. BUS II which is in locations 5620/7777 will remain in memory only if no more than 256 POINTS/SCAN are used.*, since these would occupy locations 4000/5777 and 4000/7777, respectively.

It is sometimes more convenient to have the controller reset to BUS II at location 6500 instead of resetting to the PROGRAM at location 1052. The PROGRAM can then be started by typing "carriage return" and 1052 G. Changes of the auto restart can be made from the keyboard when in BUS II.

LOCATION	CODE	INSTRUCTION	
0014	142	JMP 1052	Auto restart at 1052
0015	052		(PROGRAM)
0014	155	JMP 6500	Auto restart at 6500
0015	100		(BUS II)

2.7.2 Loading the Tapes

If BUS II is in memory, tapes may be loaded very simply by performing the 3 steps in Sect. 2.7.5.

If BUS II is not in memory, and the BOOTSTRAP is intact, it is necessary first to load the BUS II TAPE by the procedure in Sect. 2.7.4.

If the BOOTSTRAP is not in memory it must first be loaded by the following procedure, taken from Sect. 4.21 of the SPC-12 Programming Reference Manual.

* It is written over by data in 512 or 1024.

NOTE: The switch code is down = 1, up = 0.

(1) UNLOCK key switch at the rear of the SPC-12.

(2) Set R/I switch down.

(3) Set MEMORY GUARD switch up.

(4) Set SAVE-I switch up.

(5) Set the 3 register switches to X (001_2).

(6) Set the 12 data switches to 6400_8 (STB B, X).

(7) Press ENTER switch and observe 6400 in the data lights.

(8) Press LOAD-I switch.

(9) Set SAVE-I switch down.

(10) Set the 12 data switches to 777_8.

(11) Press ENTER and observe 777 in X by the data lights.

(12) Set the 3 register switches to B (101_2).

(13) Set data switches 0 - 7 to 004_8, the first code in the Table I.

(14) Press ENTER switch.

(15) Press STEP switch. The code 004 is now stored in location 1000.

(16) Repeat steps 13-15 with the other codes in Table I until all have been entered into memory.

TABLE I

MEMORY LOCATION (OCTAL)	CONTENTS 0	1	2	3	4	5	6	7
1000	004	111	120	014	045	131	142	003
1010	010	164	004	113	300	010	374	014
1020	040	010	133	010	377	100	131	142
1030	021	010	266	131	142	015	000	130
1040	010	111	004	210	117	131	142	003
1050	140	264						

2.7.3 Bootstrap Confirmation

Confirmation that the correct codes are in the BOOTSTRAP may be made as follows:

(1) Repeat steps 1-12 of Sect. 2.7.2 with the exception of step(6) for which 7400 (LDB B,X) should be entered on the data switches.

(2) Press the STEP switch. The codes displayed on the data lights should match Table I. The B register contains the code and the X register its location.

2.7.4 To Load BUS II

The BOOTSTRAP program loads the original version of the LOADER program in locations 264/476. This in turn is used to load new versions of the TTY I/O, LOADER, PUNCHER, and MODE CONTROL subroutines along with BUS II in the upper part of memory. To load BUS II from the BOOTSTRAP, proceed as follows:

NOTE: The switch code is down = 1, up = 0.

(1) UNLOCK key switch at the rear of the SPC-12.

(2) Set R/I switch down.

(3) Set MEMORY GUARD switch up.

(4) Set SAVE-I switch up.

(5) Set the 3 register switches to P (100_2).

(6) Set the 12 data switches to 2100_8 (NO-OP).

(7) Press ENTER, and observe 2100_8 in the data lights.

(8) Press LOAD-I switch.

(9) Set the 12 data switches to 777_8.

(10) Press ENTER and observe 777 in the data lights for P.

(11) Set R/I switch up.

(12) Press STEP switch.

(13) Switch the TELETYPE to LINE, and its reader to FREE.

(14) Place the BUS II TAPE in the reader, with the first double hole punch directly over the reader probes.

(15) Switch the reader to START.

Correct loading of the tape is confirmed at each check-sum by a typed L and 6 rub-outs on the teleprinter.

(16) Push the controller RESET when the tape has finished loading. This causes transfer from the original LOADER to the new version of BUS II.

2.7.5 To Load Program

The PROGRAM TAPE must now be reloaded, because locations 264/476 have been destroyed by the original LOADER.

(1) Confirm that the TELETYPE is on LINE and that the controller is in BUS II by pressing the RETURN key; it should give both a carriage return and a line feed.

(2) Place the blank leader of the PROGRAM TAPE in the reader with the switch at FREE.

(3) Switch the reader to START.

After the PROGRAM TAPE is loaded, the controller will be in BUS II; to initiate the program, it should be RESET.

SECTION 3

HARDWARE SYSTEM

3.1 PULSE GENERATOR

The pulse generator and rf system are contained in the oval box shown in Fig. 8. On the top of the box may be seen the oscilloscope sampling head, meters to set the step recovery bias currents, and the dielectric sample holder, which is also shown in Fig. 9. Since this system was required to have a 10 nsec time window instead of the 2.5 nsec window of the SRRC LINC system, the delay lines had to become four times longer. Rather than continuing to use precision air lines, which would have had to extend some 15 feet, the decision was made to use RG 331 0.5 inch diam. semiflexible foam dielectric cable, and this is wound inside the box in a race-track form. Since the low-loss RG 331 cable was fairly bulky, it was only used for the fastest pulses; slower pulses being delayed with 0.141" diam. semiflexible cable. These cables may be seen inside the box, in Fig. 10, and the layout may be compared with the circuit diagram of Fig. 11. In Fig. 10, reading from right to left, are seen the stripline units containing the avalanche transistor, the -0365 step recovery diode, and the -0386 step recovery diode, respectively.

The principle of the step recovery diode pulse generator follows closely that of the description in Sect. 3 of the Interim Report. A 2N3301 avalanche transistor produces a pulse with a risetime of about 1 nsec, and this risetime is sharpened by two successive step recovery diodes to be about 220 psec and 90 psec, respectively, the final waveform being approximately impulse-like and about 5 V in amplitude. This pulse than passes through a padding attenuator and two power dividers, which connect to the stubs providing the timing markers V_x and V_y of Fig. 1. After passing through the sampling head, the pulse either is connected into the room temperature system, as is seen in Figs. 2 and 8, or into the high temperature holder as described in Sect. 6.

Bias currents for the step recovery diodes are adjusted to be 2 mA for the -0365 and 5 mA for the -0386 using potentiometers on the top of the

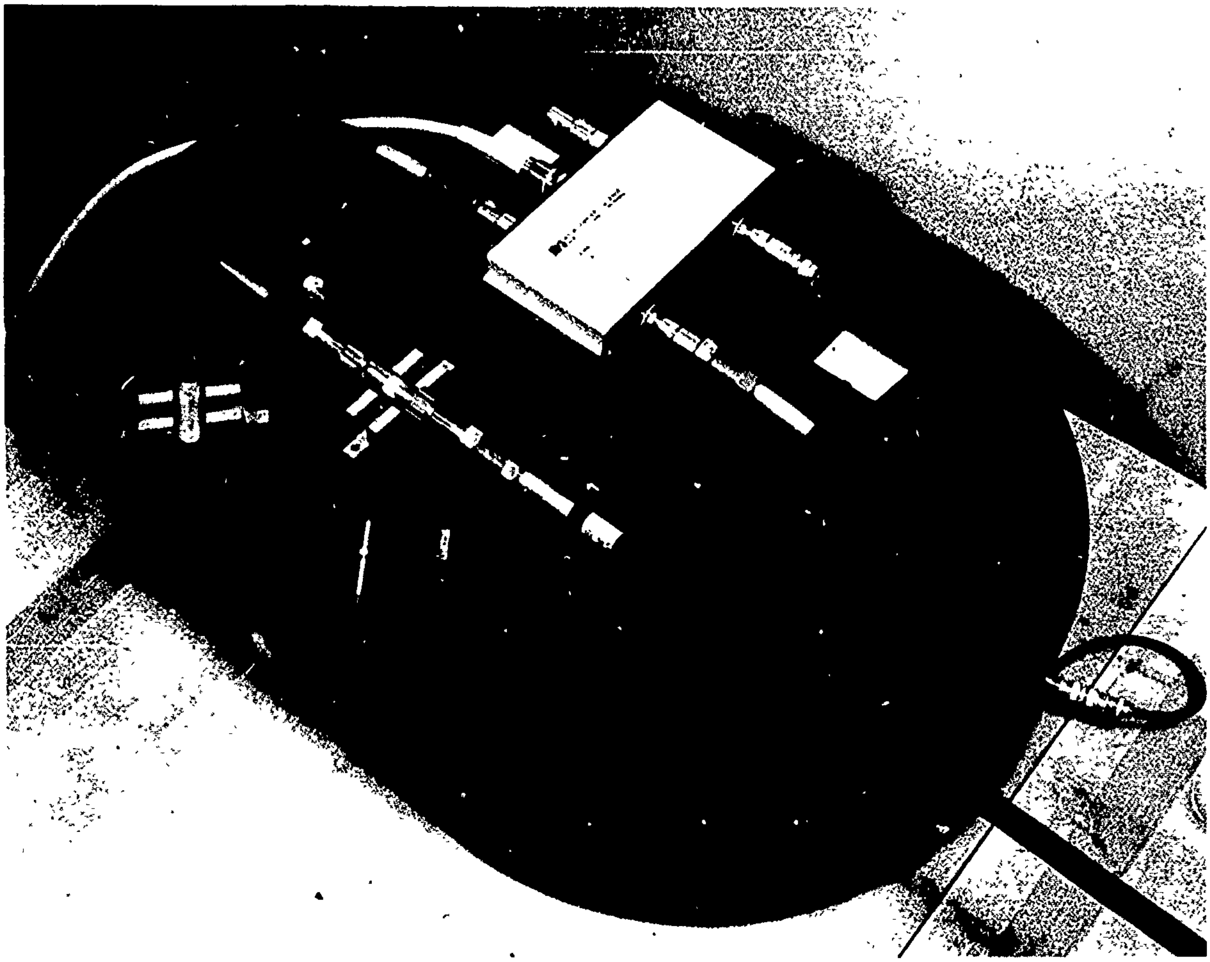


FIG. 8 Pulse generator unit.

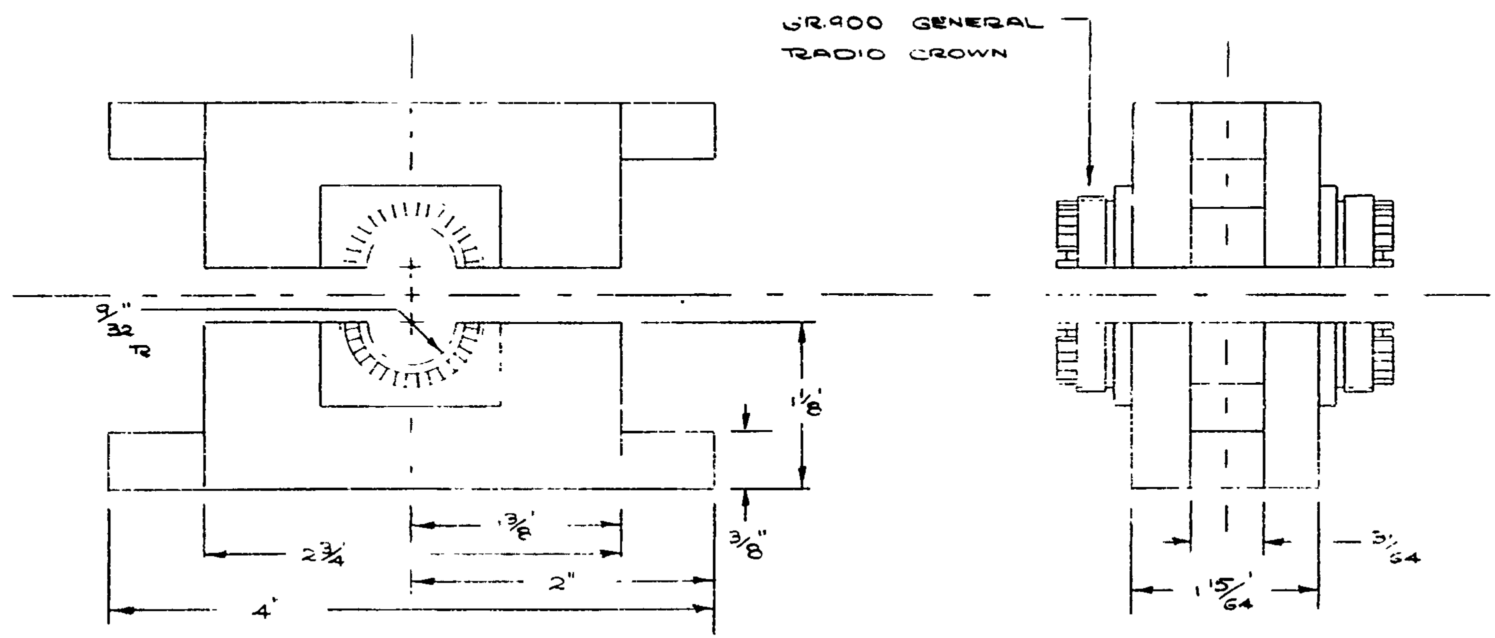


FIG. 9 Normal sample holder.

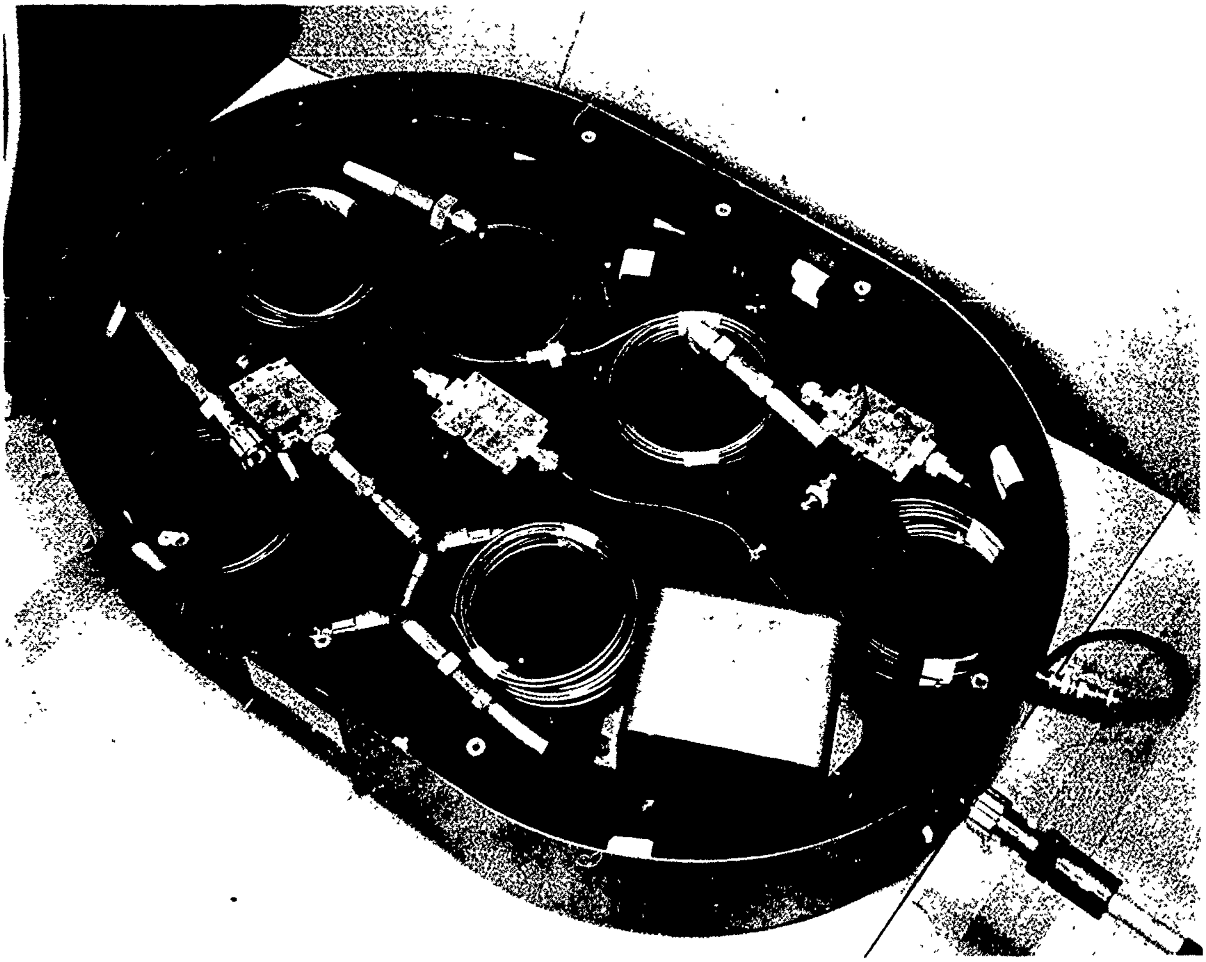


FIG. 10 Interior of pulse generator unit.

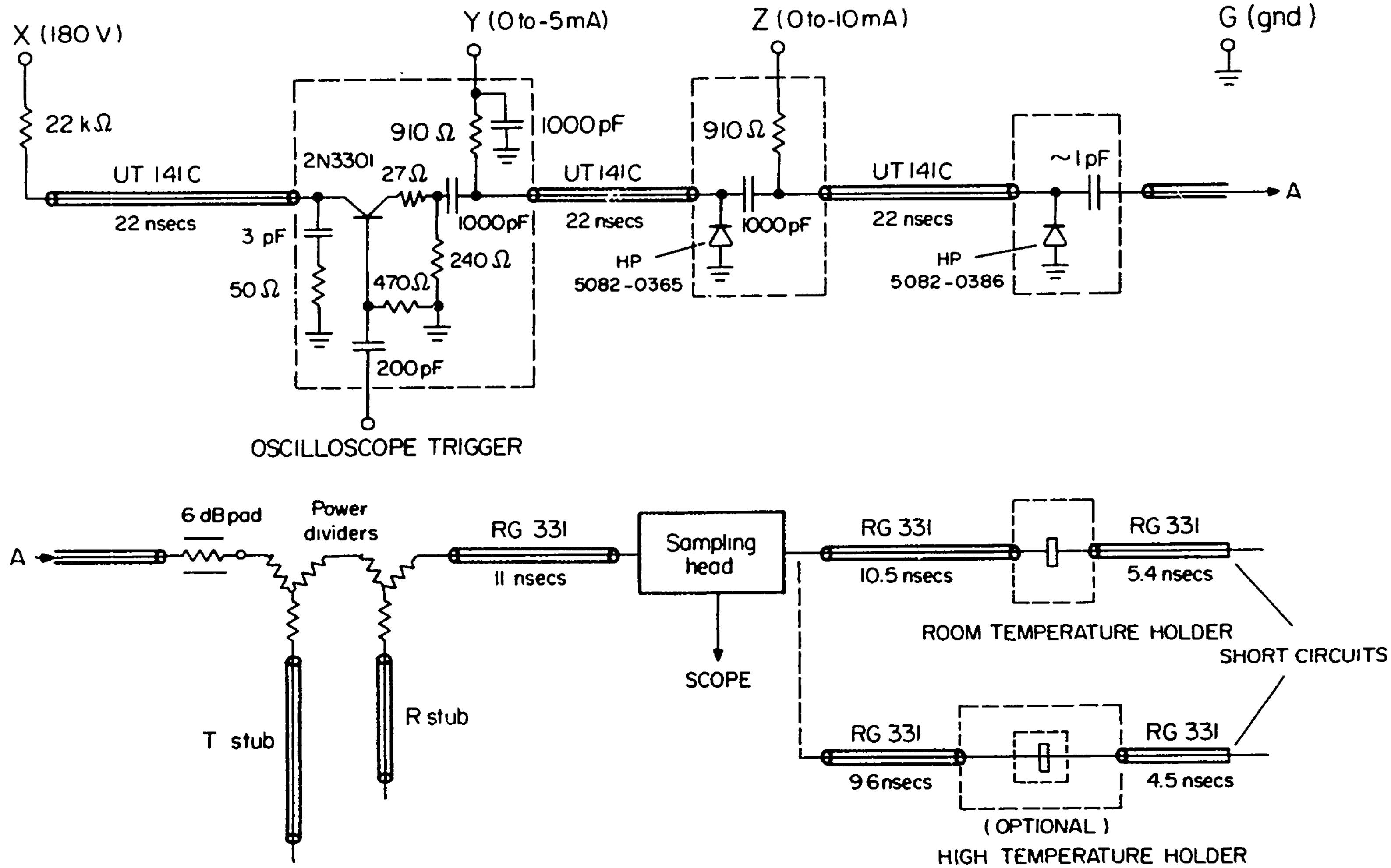


FIG. 11 Schematic diagram of pulse generator.

pulse generator unit. The power supplies in the unit are shown in Fig. 12, where it is seen that the bias currents are provided from a heavy duty 12 V dry battery. The battery supply is automatically disconnected by a relay when the 115 V ac power is shut off.

3.2 INTERFACE EQUIPMENT

The SPC-12 controller is connected through interfacing equipment to the other instruments in the measurement system, and to the control panel. A brief block diagram description follows.

Input channels to the SPC-12 are shown in Fig. 13. Data lines to and from the SPC-12 are connected through the CIT card, while other input and output channels are connected through the FIT card. There are eight 12-bit input data channels, and a particular channel is selected by the computer by gating one channel of one of the two 4-input multiplexers. Data input channels 0, 1 and 2 are concerned with sensing the switch positions on the control panel, and when any of the panel pushbuttons is pressed, the event is stored in a set of latches, eventually being interrogated by input to data channel 6. The latches are all reset by a pulse from the SPC-12 on control pulse line 5. Status indications from the tape recorders, such as a broken tape flag, are similarly input through resettable latches to data input channel 3. A level from the tape recorder indicating that an inter-record gap has been completed is monitored on the SPC-12 test function line 0. Data input channels 4 and 5 accept binary-coded-decimal (BCD) data from the digital voltmeter; a software routine converts this into binary numbers. The encode command to the DVM, requiring a new conversion to be made, is produced from control pulse line 3 and stretched in a monostable multivibrator to 120 μsec.

Output channels from the SPC-12 are shown in Fig. 14. Data output channels 0, 1 and 2 each feed a set of holding latches; the digital contents of these latches are decoded in 3 digital - analog converters; the resulting analog voltages summed in an operational amplifier, and used to drive the X position on the sampling oscilloscope. DAC1 and DAC2 are 10-bit, and DAC3 is 12-bit; each DAC output is also available at the rear of the equipment rack,

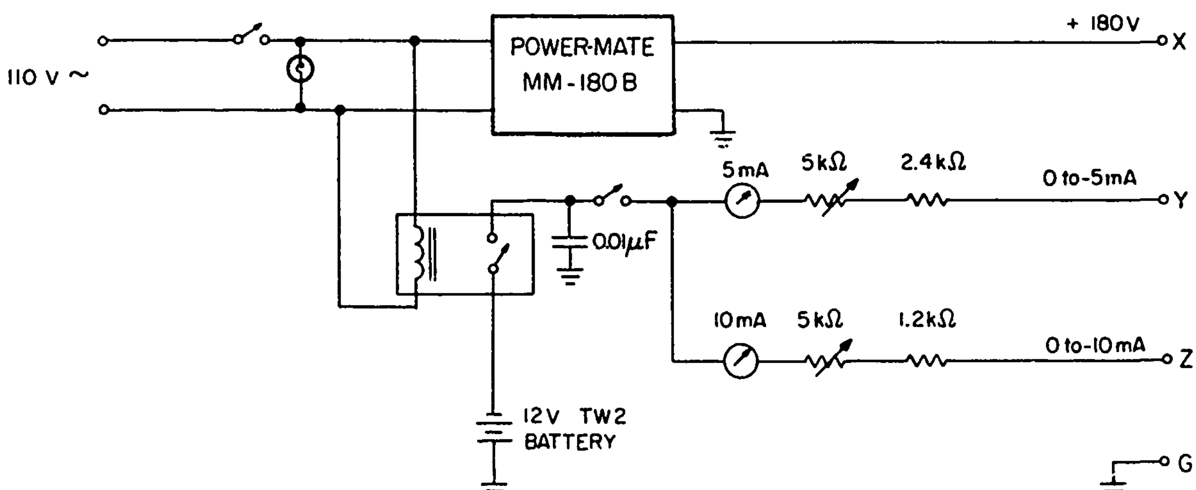


FIG. 12 Pulse generator power supplies.

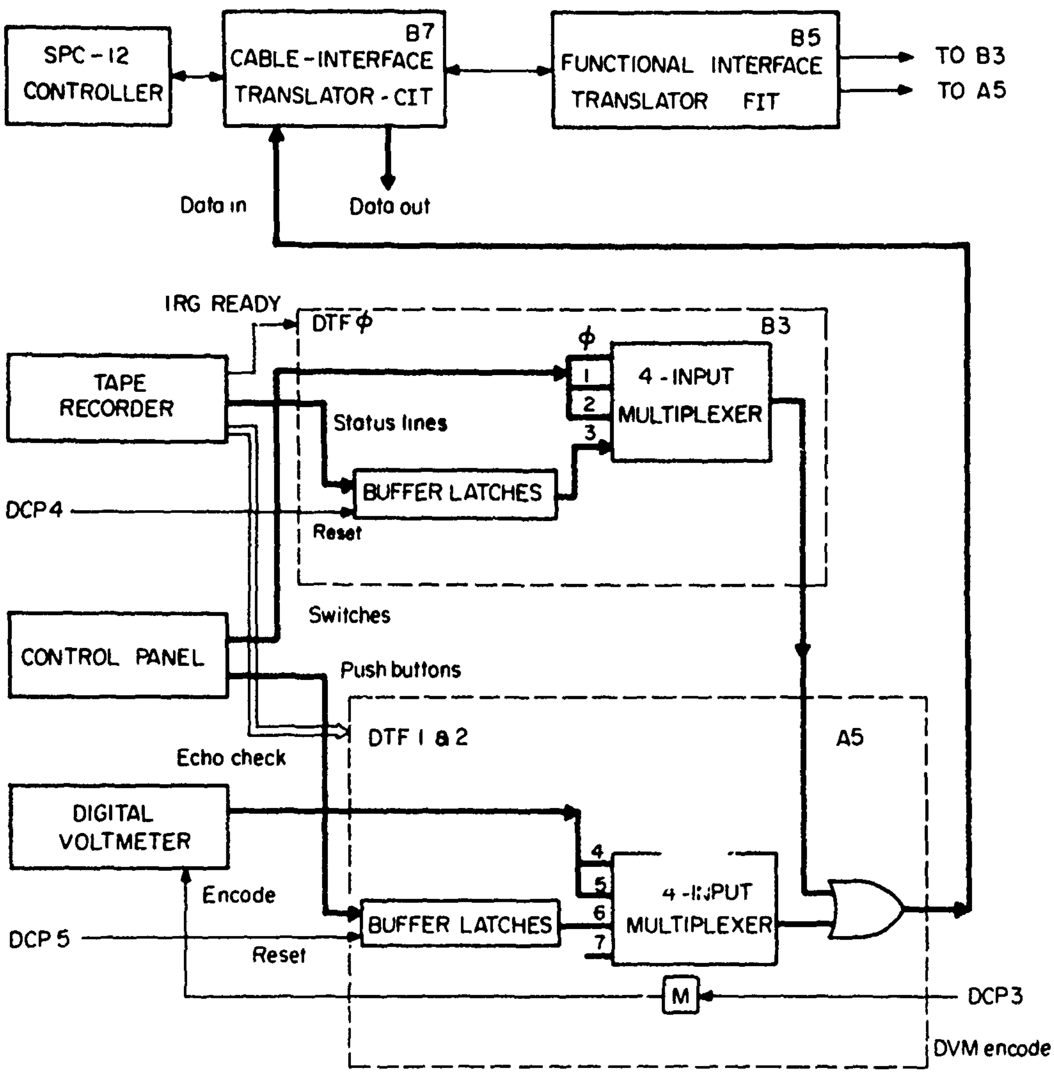


FIG. 13 SPC-12 input channels.

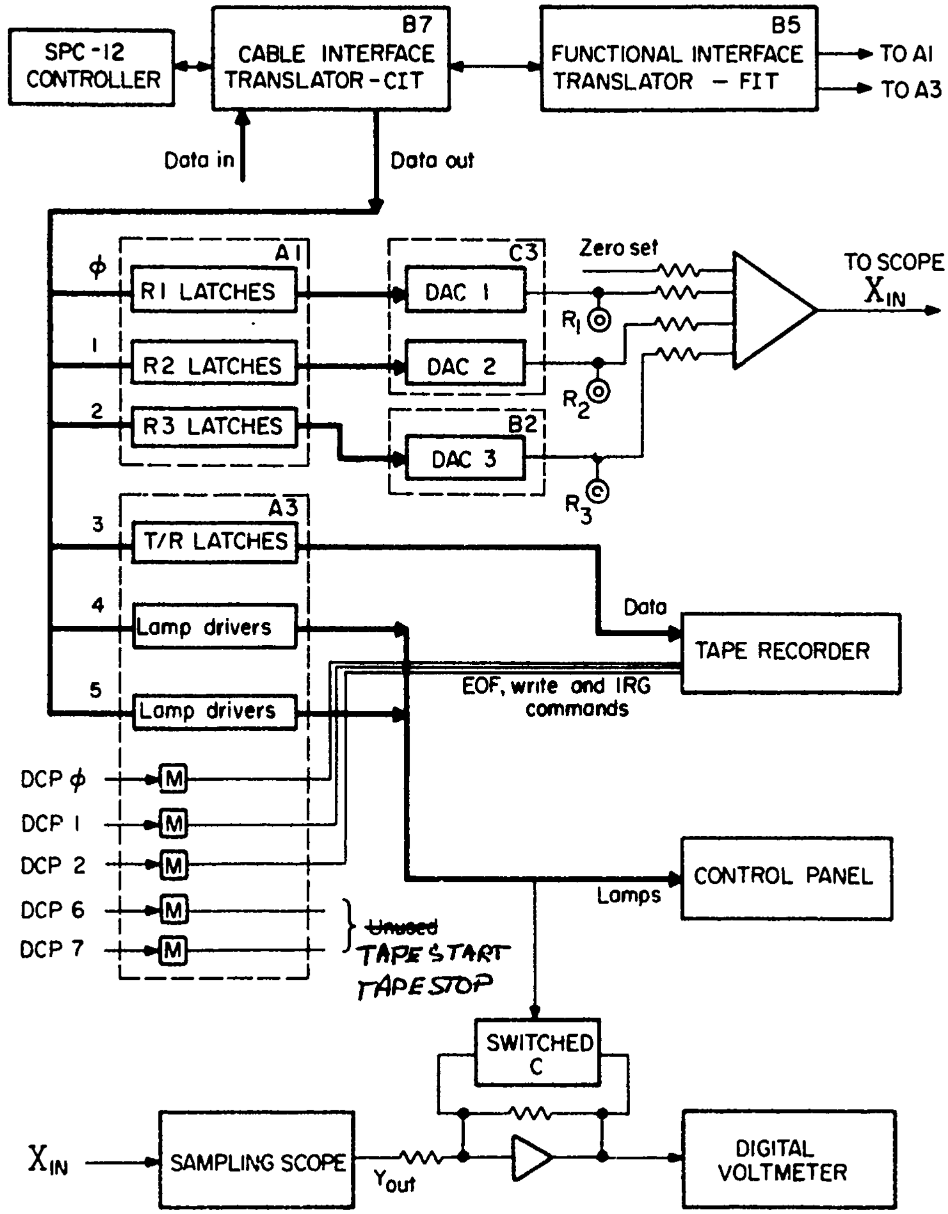


FIG. 14 SPC-12 output channels.

and DAC2 and DAC3 are normally used to drive the X and Y channels of an auxiliary oscilloscope, to provide an intermediate display of waveforms. Data output channel 3 drives a set of latches which are connected in turn to the data input channel of the tape recorder. Once data has been loaded on to these latches, a pulse on control pulse line 1, again stretched to 120 μsec in a one-shot, commands the recorder to write, and to step the tape forward. Other control pulses on lines 0 and 2 command end-of-file marks and inter-record gaps respectively. Data output channels 4 and 5 connect to latches and high current drivers, which light signal lamps on the control panel. One of the lines is used to control a reed relay, which alters the risetime of an amplifier circuit connected between the sampling oscilloscope Y output, and the digital voltmeter. In this way it can vary the integration time to smooth the oscilloscope signal.

All of the interface circuitry is mounted on plug-in cards in the SPC-12 interface unit, and the card locations are indicated in Figs. 13 and 14. The operational amplifiers are mounted on the control panel adjacent to the relevant BNC connectors. Schematic diagrams of the digital interface circuitry are given in Figs. 15 through 22. The analog signal processing is shown in Fig. 23. The digital voltages are standard TTL levels. Positive true ~~tone~~ levels are indicated by a plus sign and zero true ~~tone~~ levels are indicated by a minus sign.

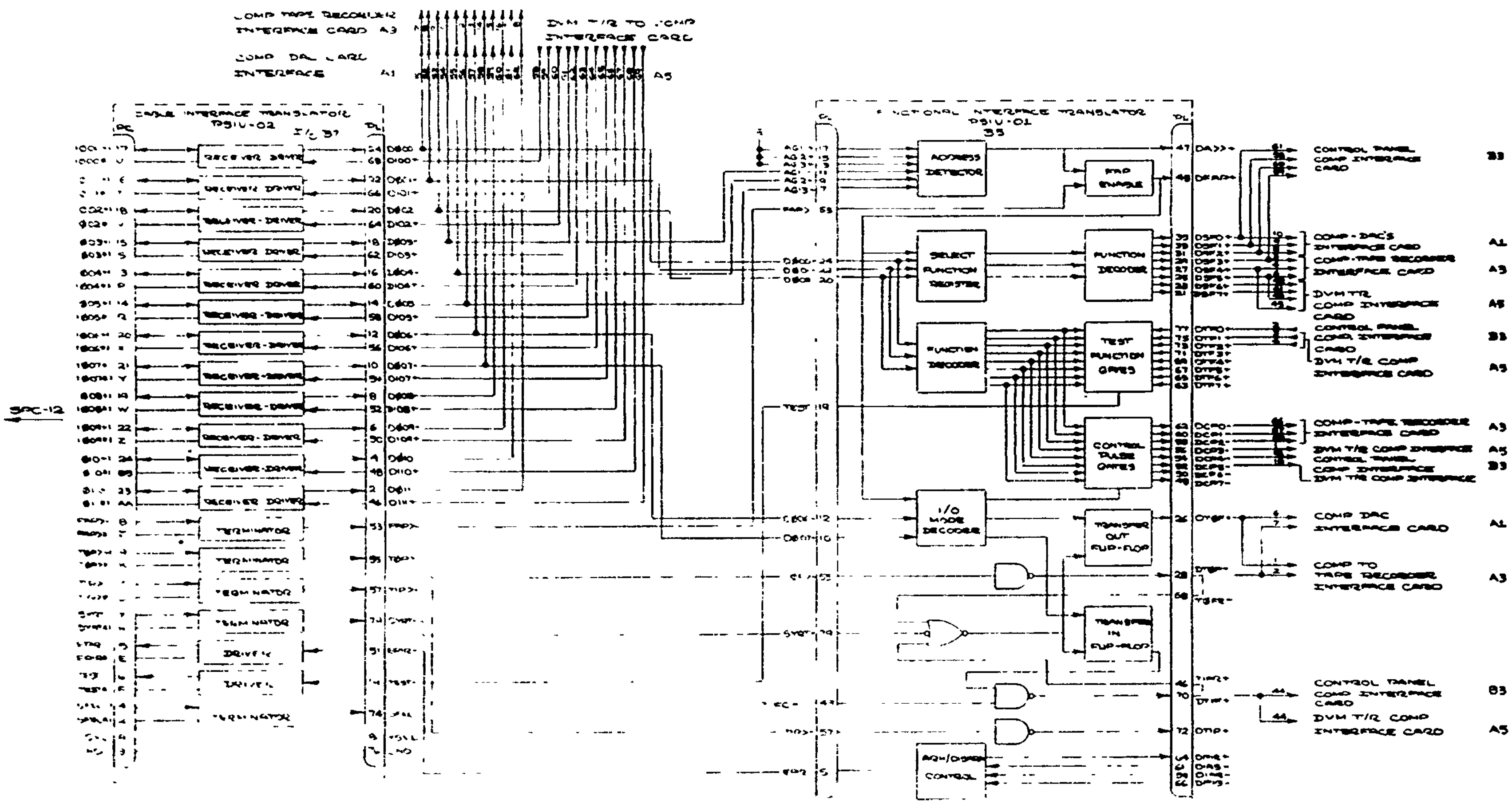


FIG. 15 Computer interface functional diagram for Cable Interface Translator (CIT) and Functional Interface Translater (FIT).

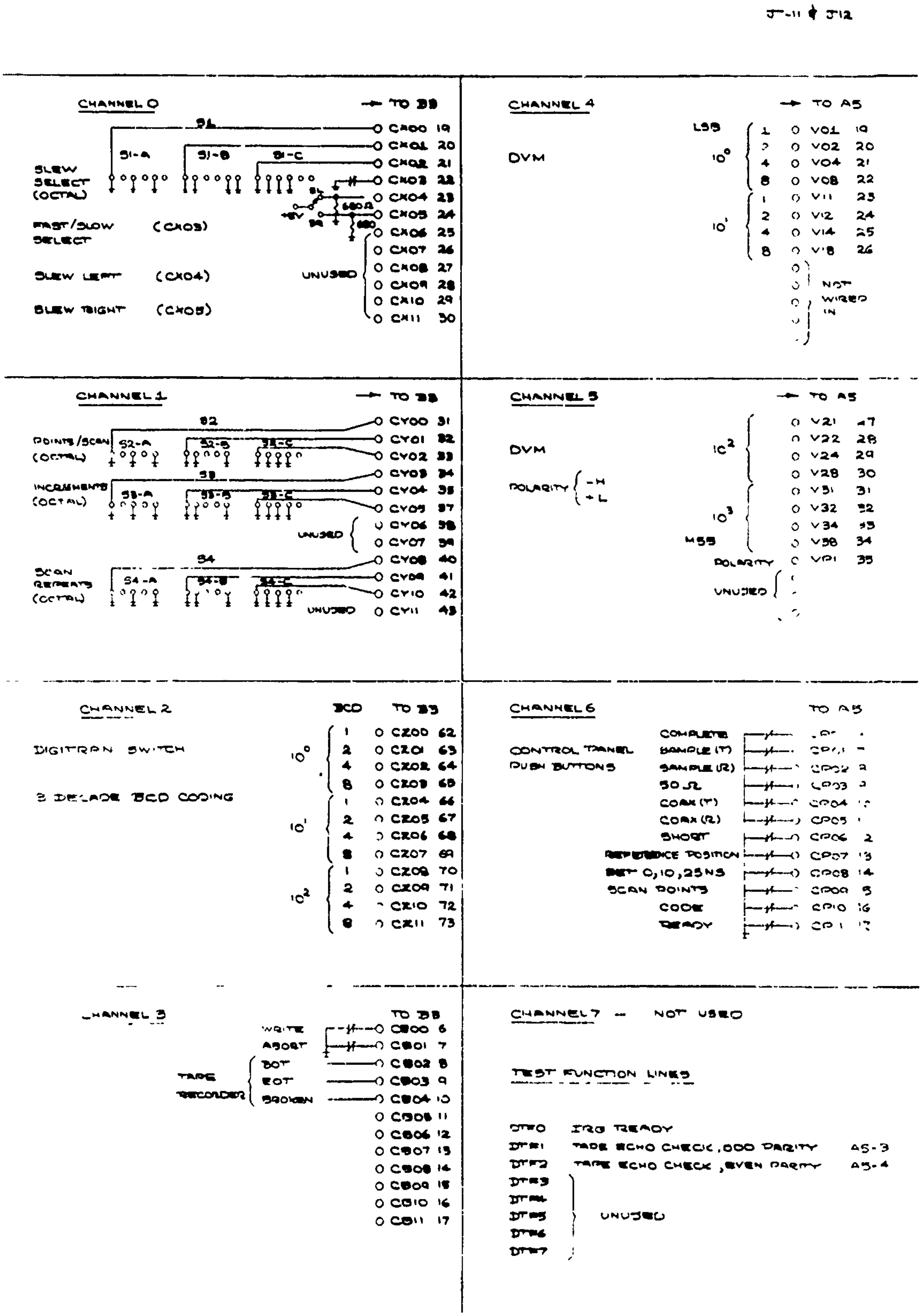


FIG. 16 Data input channels.

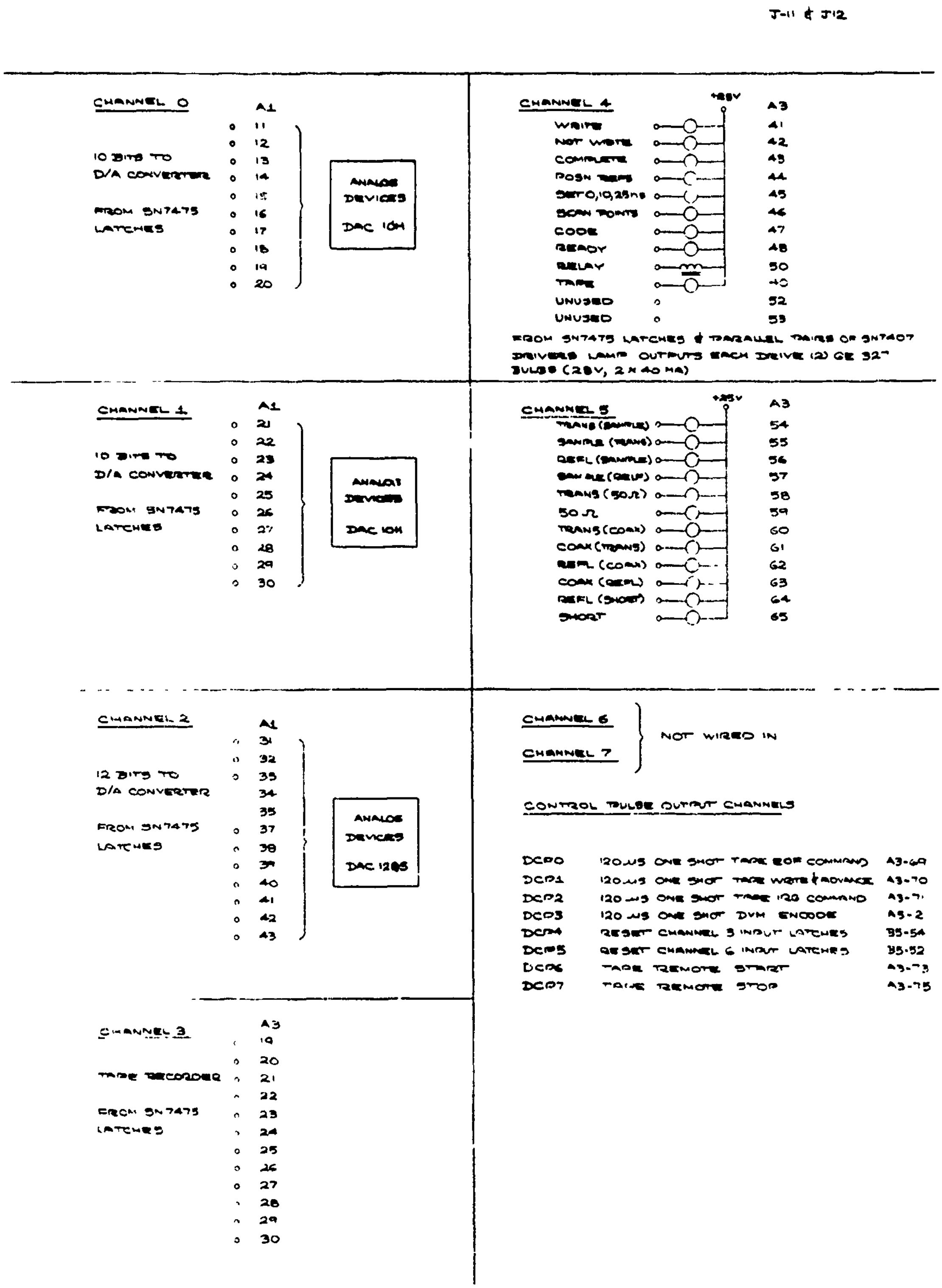


FIG. 17 Data output channels.

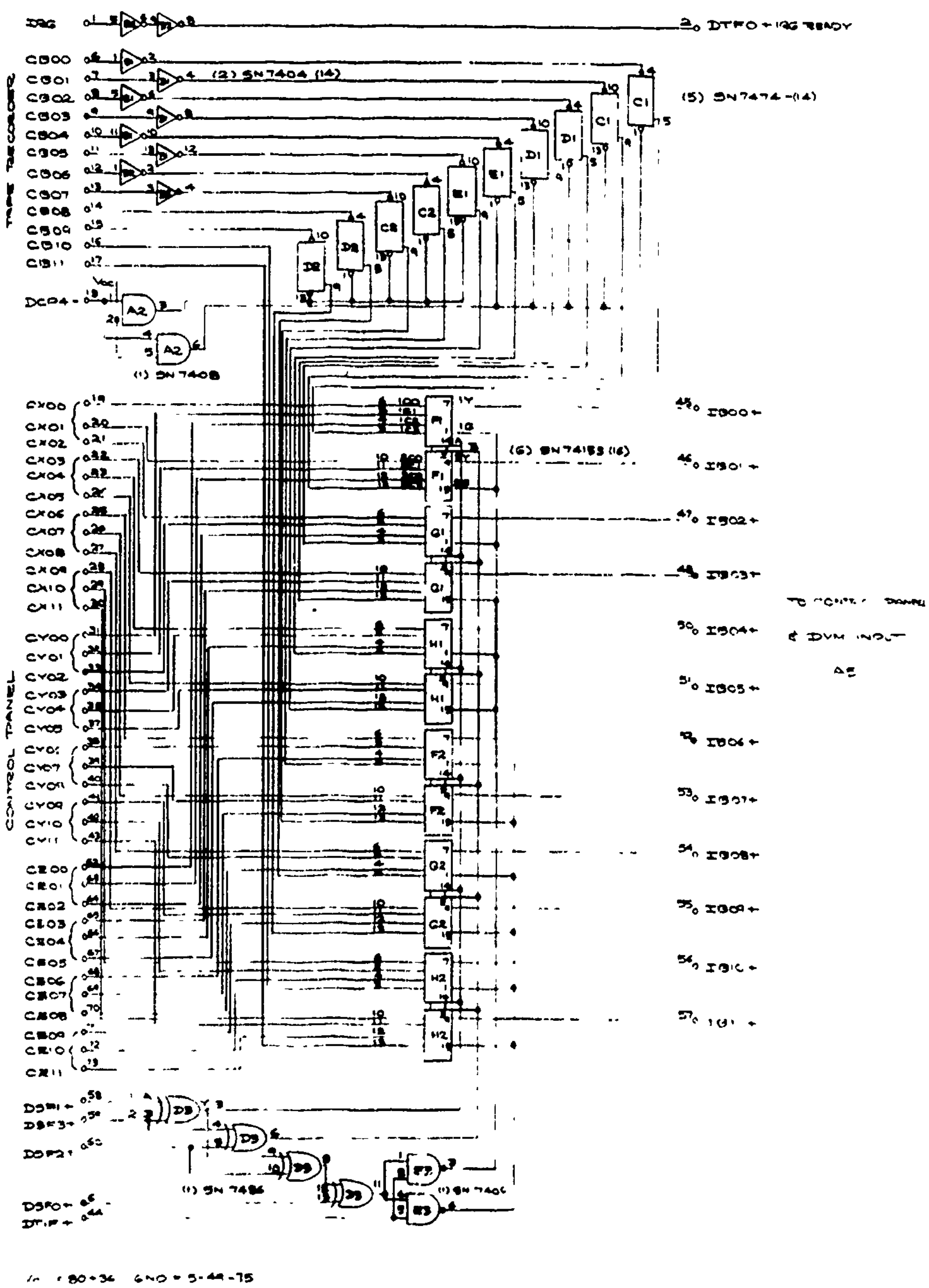


FIG. 18 Control panel and tape recorder unit.

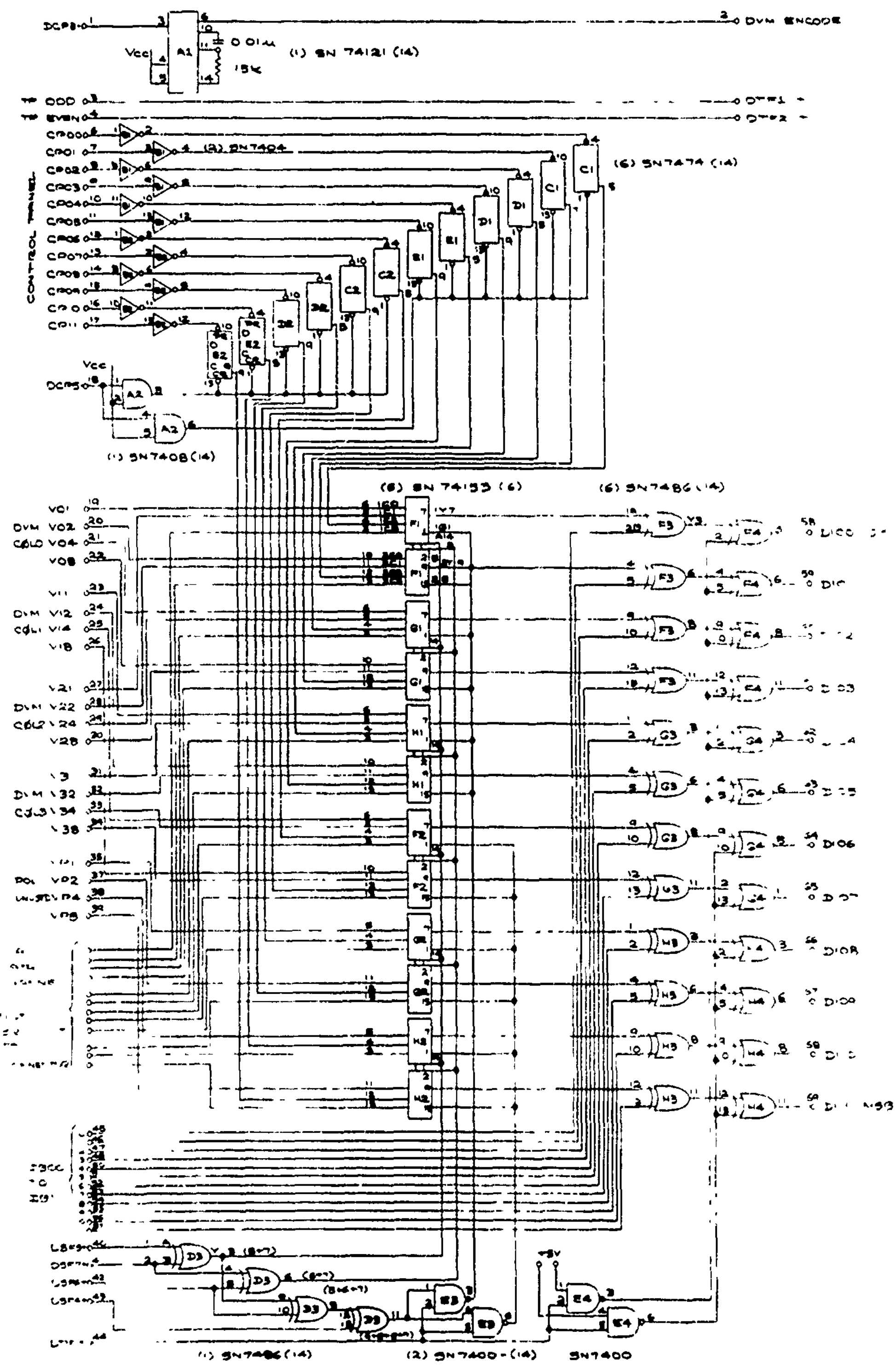


FIG. 19 Control panel and DVM input.

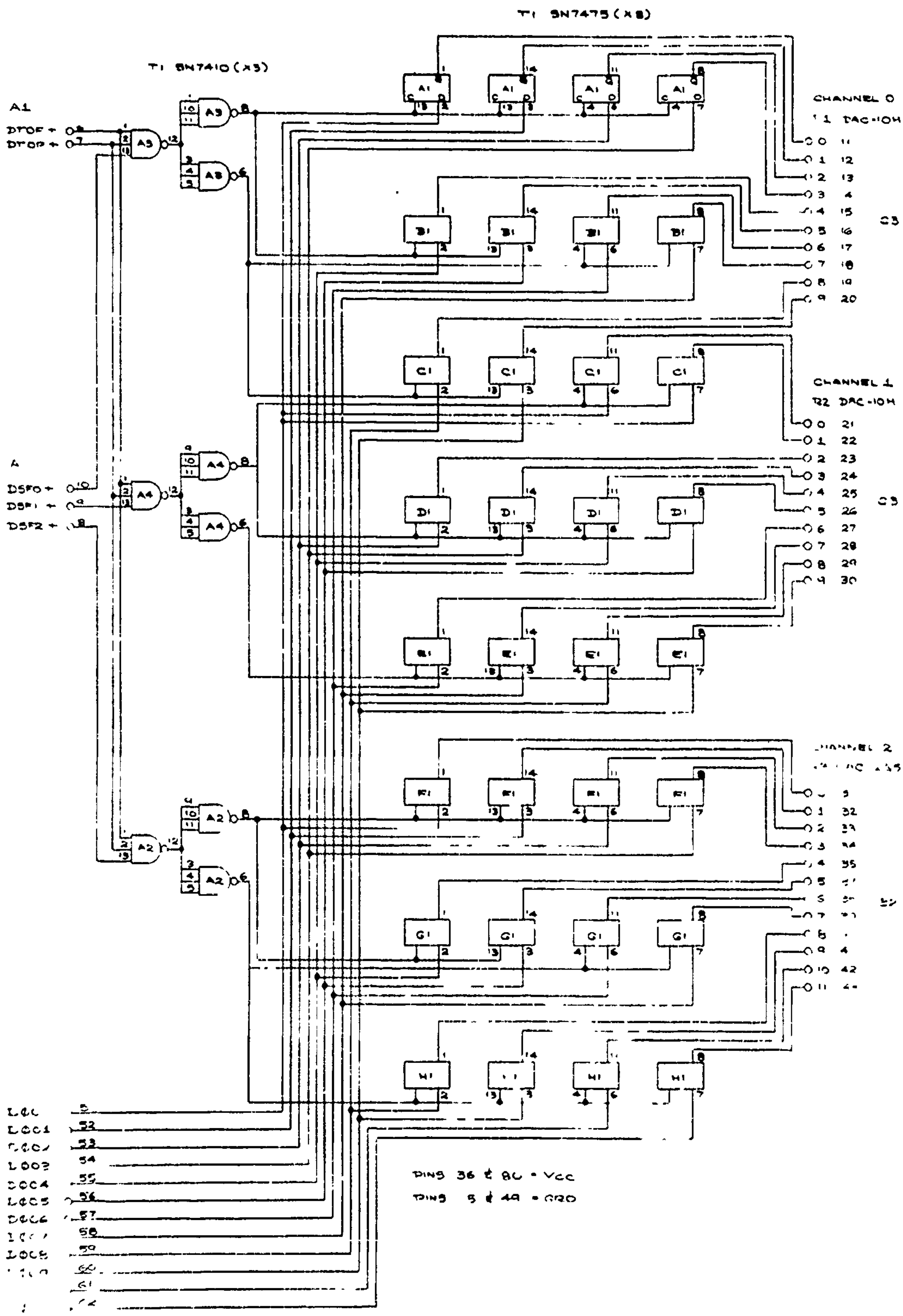


FIG. 20 Output to DAC's.

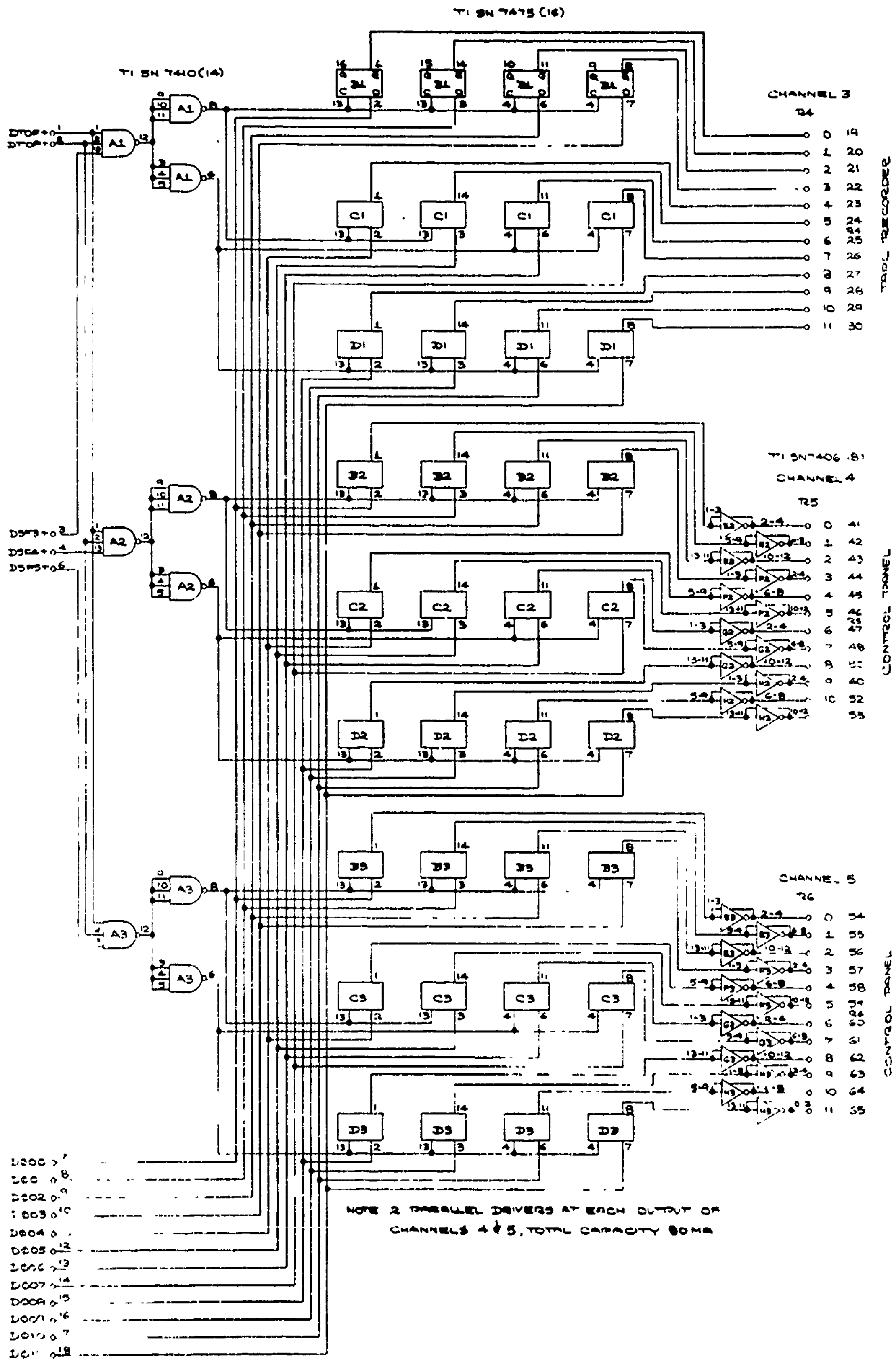


FIG. 21 Output to control panel and tape recorder.

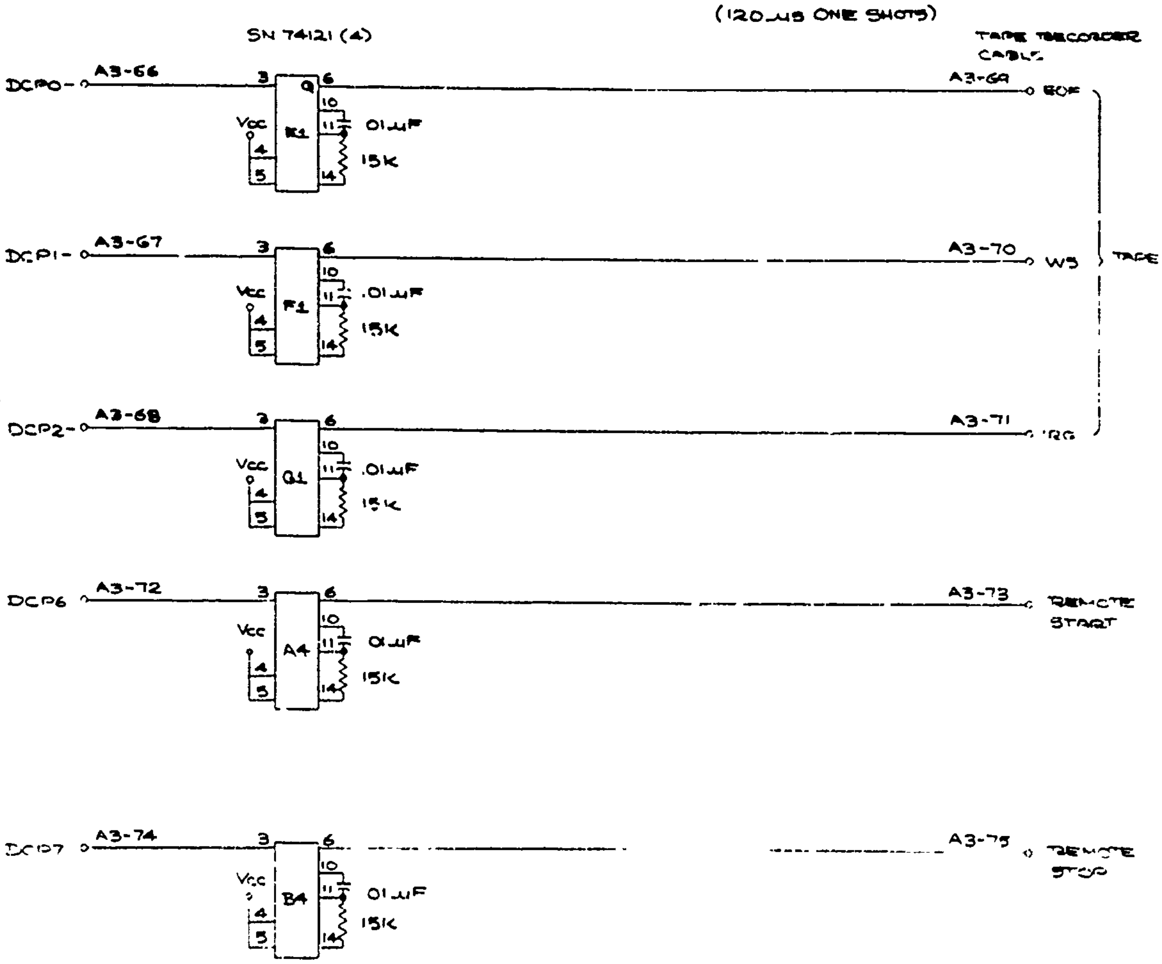


FIG. 22 Control pulse output channels.

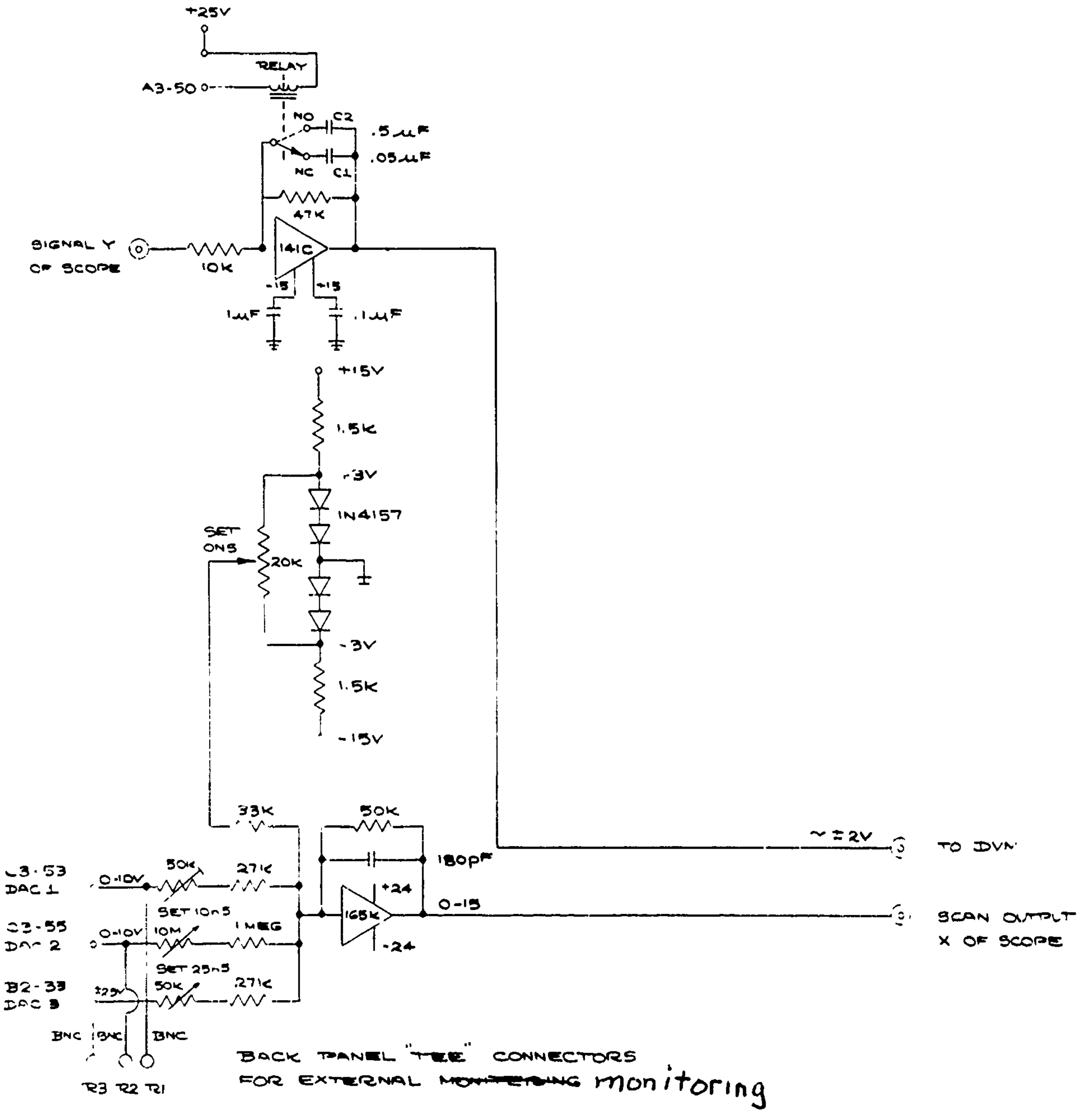


FIG. 23 DAC and DVM signal processing.

SECTION 4

SPC-12 PROGRAM

The essential elements of the SPC-12 program are given in simplified flow diagrams in this section.

A measurement program was designed that is versatile, yet simple and reliable in its operation. The program is a dialogue between operator and machine; the machine calls for certain operations to be performed by lighting buttons, and the operator pushes these buttons after he has set up the conditions the machine is requesting. The details of instruction to the operator are contained in Sect. 2.4.

The SPC-12 has an automatic start-up feature, which is used to initiate the program when the power is turned on. The controller automatically performs the instruction in location 14 when turned on, and this location contains an instruction to jump to the beginning of the master program at location 1052. (All memory locations are given in octal.)

The memory of the SPC-12 is shared equally between program and data. The lower half of memory contains the program, and the upper half is used for data. There are two areas of significant size in the lower half of memory which are empty, and available for use in expanding the program. They are location 634/756 and 2336/2447. An executive program known as BUS II that may be stored in the upper part of memory has been supplied on paper tape. It provides input/output routines for the teletype and enables changes to be made in the program. When the BUS II tape is loaded it contains a jump to 6500 in location 14, which will cause the SPC-12 to be under the control of BUS II when turned on or reset. Memory changes can be made in the program using BUS II by following the instructions in Sect. 4.34 of the SPC-12 Programming Manual BUS II will remain in memory until written over by data.

The SPC-12 has a system of shared bytes, which enables a program to be written with significant saving in memory space, and full use has been made of this feature. The shared bytes occupy locations 20/117, and are discussed in Sect. 2.19 of the SPC-12 Reference Manual.

The progression by which the memory is loaded is illustrated in Fig. 24. When starting from the beginning to load the SPC-12, it is necessary first to enter a BOOTSTRAP program into locations 1000/1051 by means of the switches as described in Sect. 2.7.2. The BOOTSTRAP is used to enter a version of the LOADER into locations 264/476, which in turn is used to enter BUS II and related subroutines into the upper part of memory. Resetting the SPC-12 now gives control to BUS II that can then be used to load the program. The program covers the LOADER that was entered by the BOOTSTRAP, but does not destroy the BOOTSTRAP itself. BUS II itself is written over by data when more than 256 POINTS/SCAN are used.

The measurement program contains the following essential parts:

(1) MASTER PROGRAM
(2) SCAN routine
(3) WRITE routine
(4) DISPLAY routine
(5) SUBROUTINES
(6) STORAGE

The MASTER PROGRAM sequence is shown in Fig. 25. Figs. 25 - 29 show elements of the MASTER PROGRAM in more detail. The SCAN routine is shown in Fig. 30. The WRITE routine is shown in Fig. 31. The DISPLAY routine is shown in Fig. 32. The SUBROUTINES contain elements of the program that are used repeatedly. STORAGE space is reserved as working space and for retaining constants.

Data is in the form of 16-bit words, and the magnetic tape has 6 tracks plus parity. To produce a simple format, the 16 bit data word is followed by 32 zeros, producing eight 6-bit bytes on the tape recorder for each data word. This may be read by the computer as three 16-bit words, the latter two being discarded. If a program were developed to read 18 bits (3 bytes of tape), then this would reduce both the write time and the amount of tape used. If this were done, the WRITE routine would require a change in only one instruction: location 2727 would become 344 instead of 330.

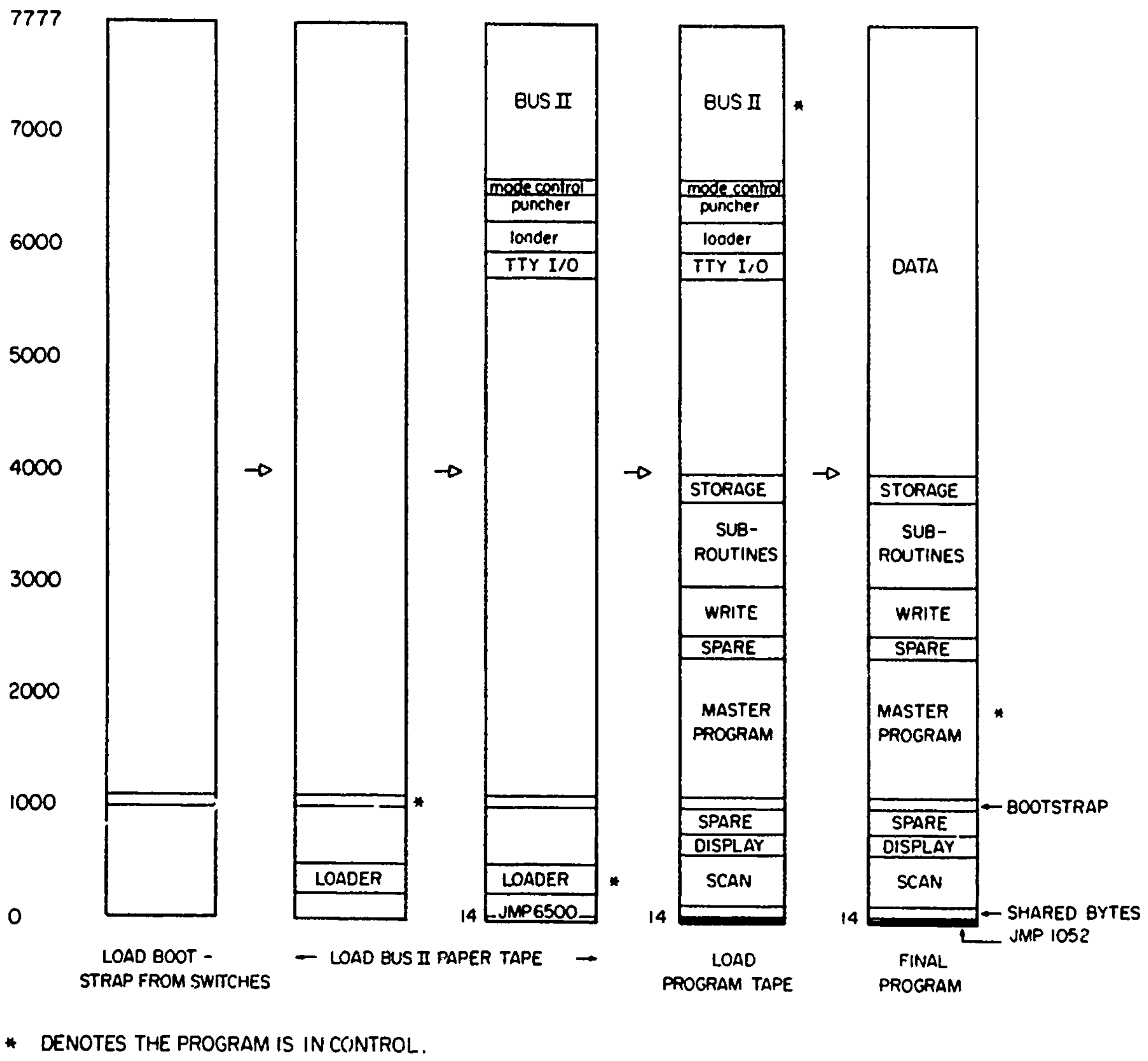


FIG. 24 SPC-12 memory loading sequence.

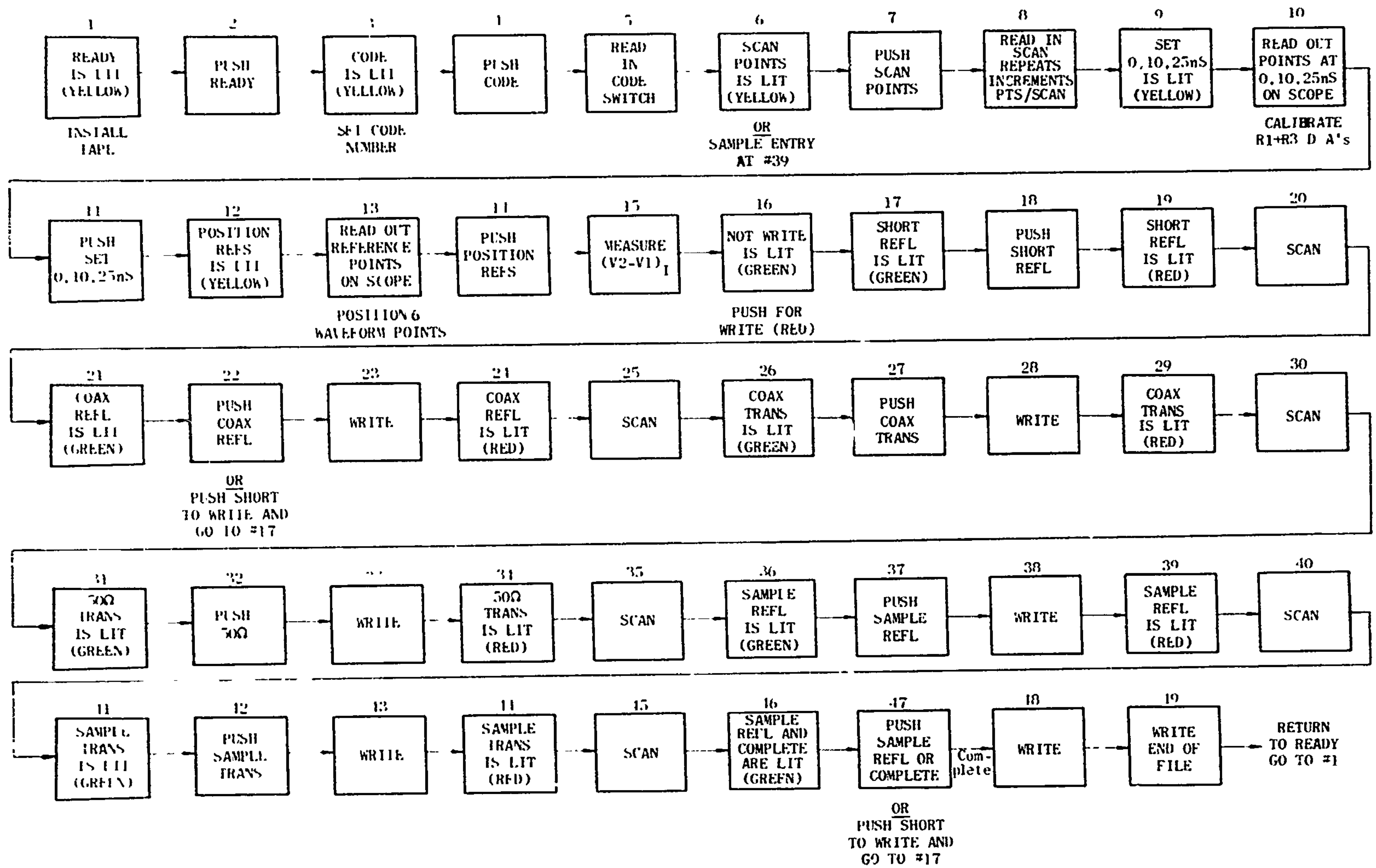


FIG. 25 Program sequence.

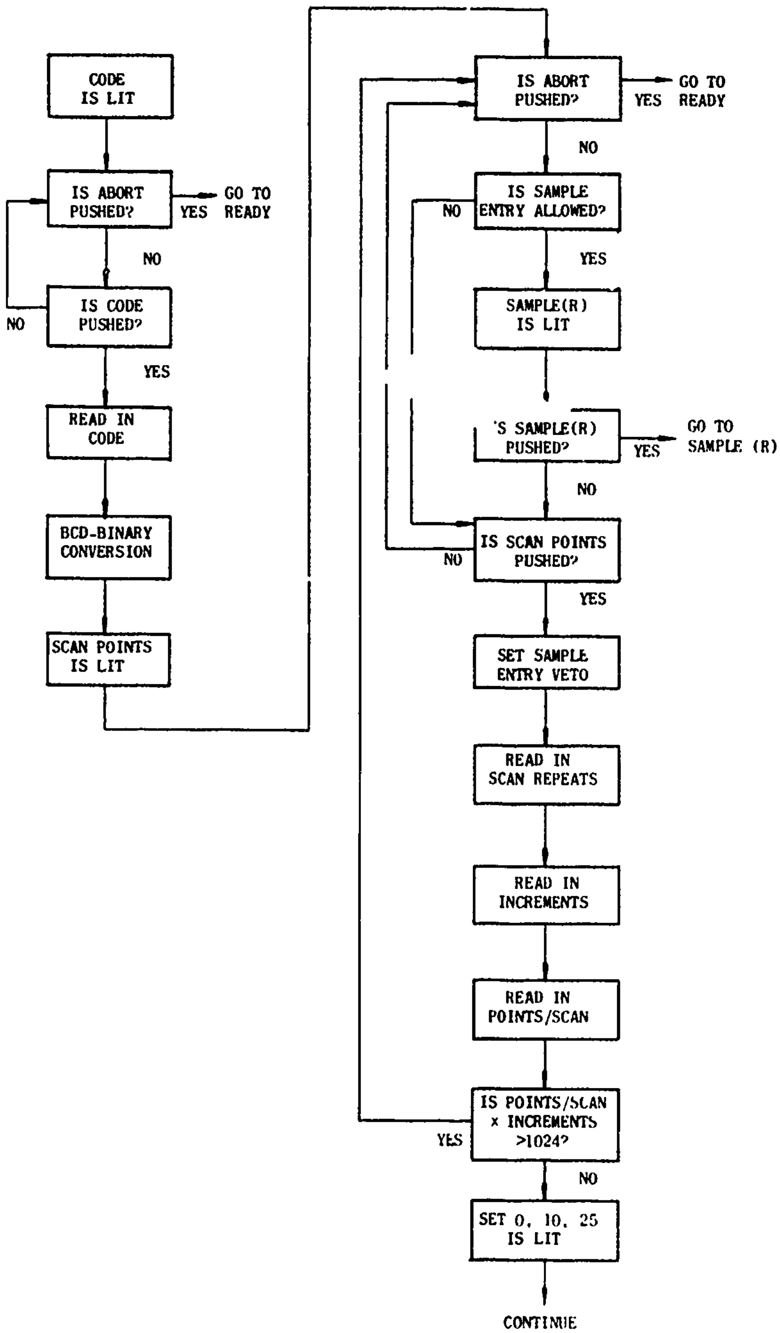


FIG. 26 CODE and SCAN POINTS read-in.

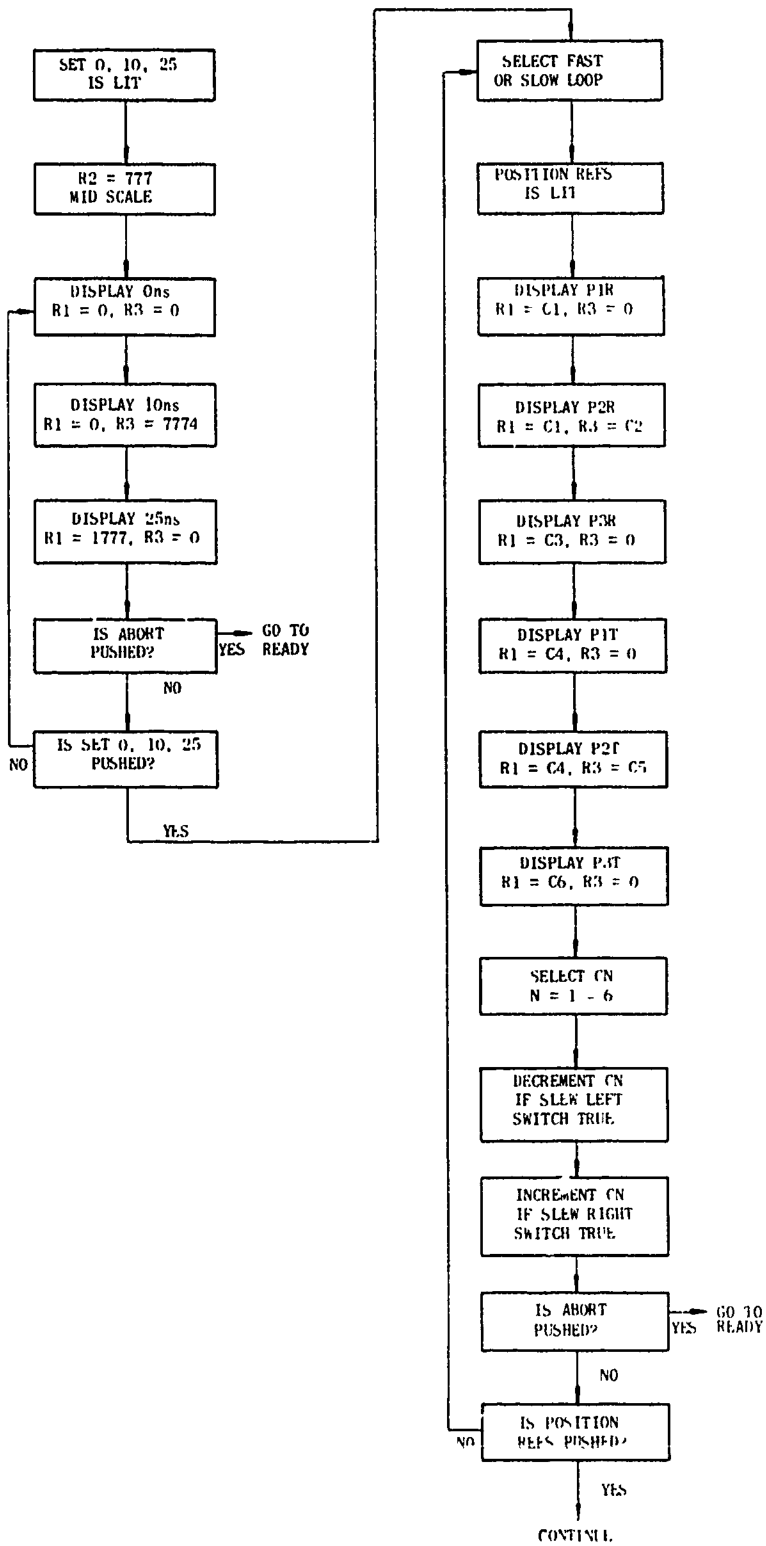


FIG. 27 SET 0, 10, 25 ns and POSITION REFS read-in.

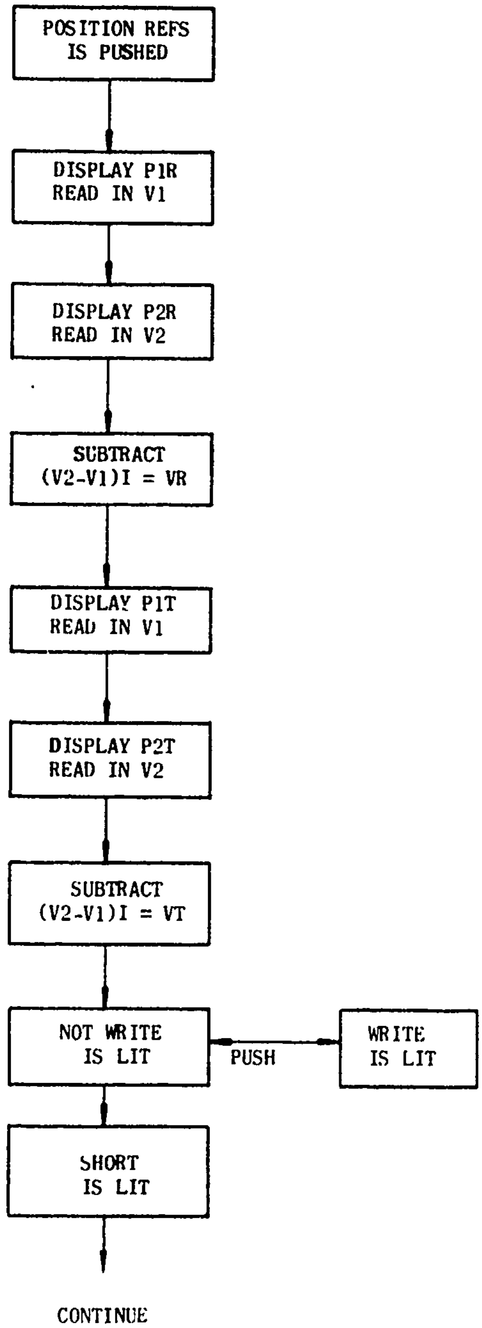


FIG. 28 Time stability, initial measurement.

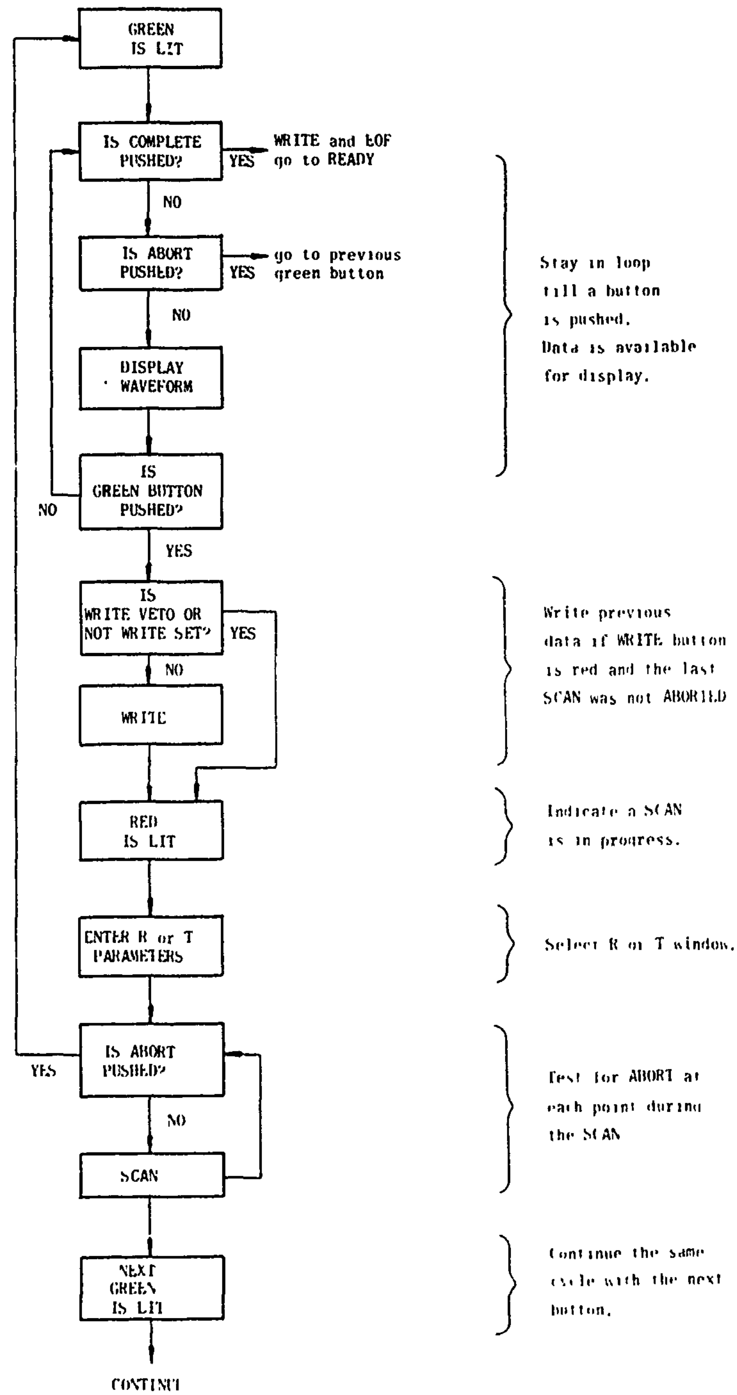


FIG. 29 Detail of cycle between green buttons.

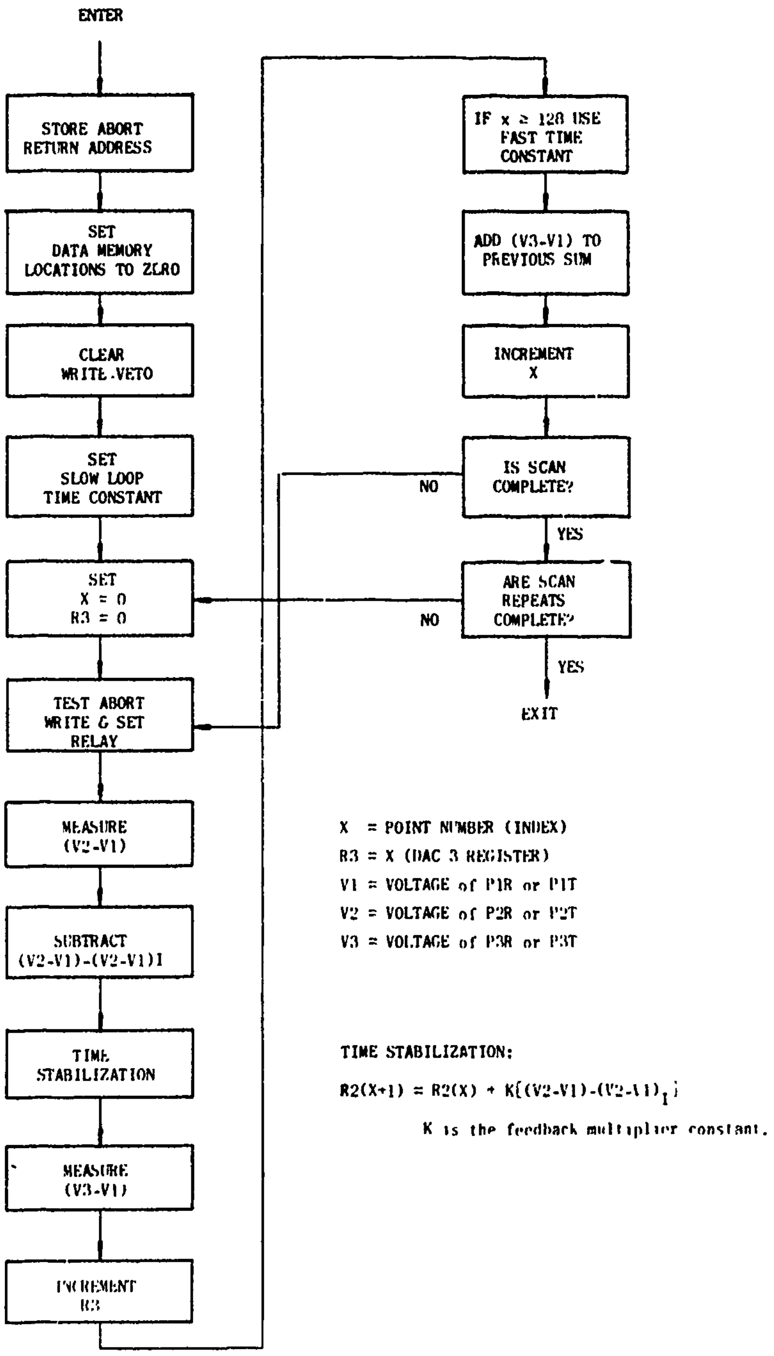


FIG. 30 SCAN routine.

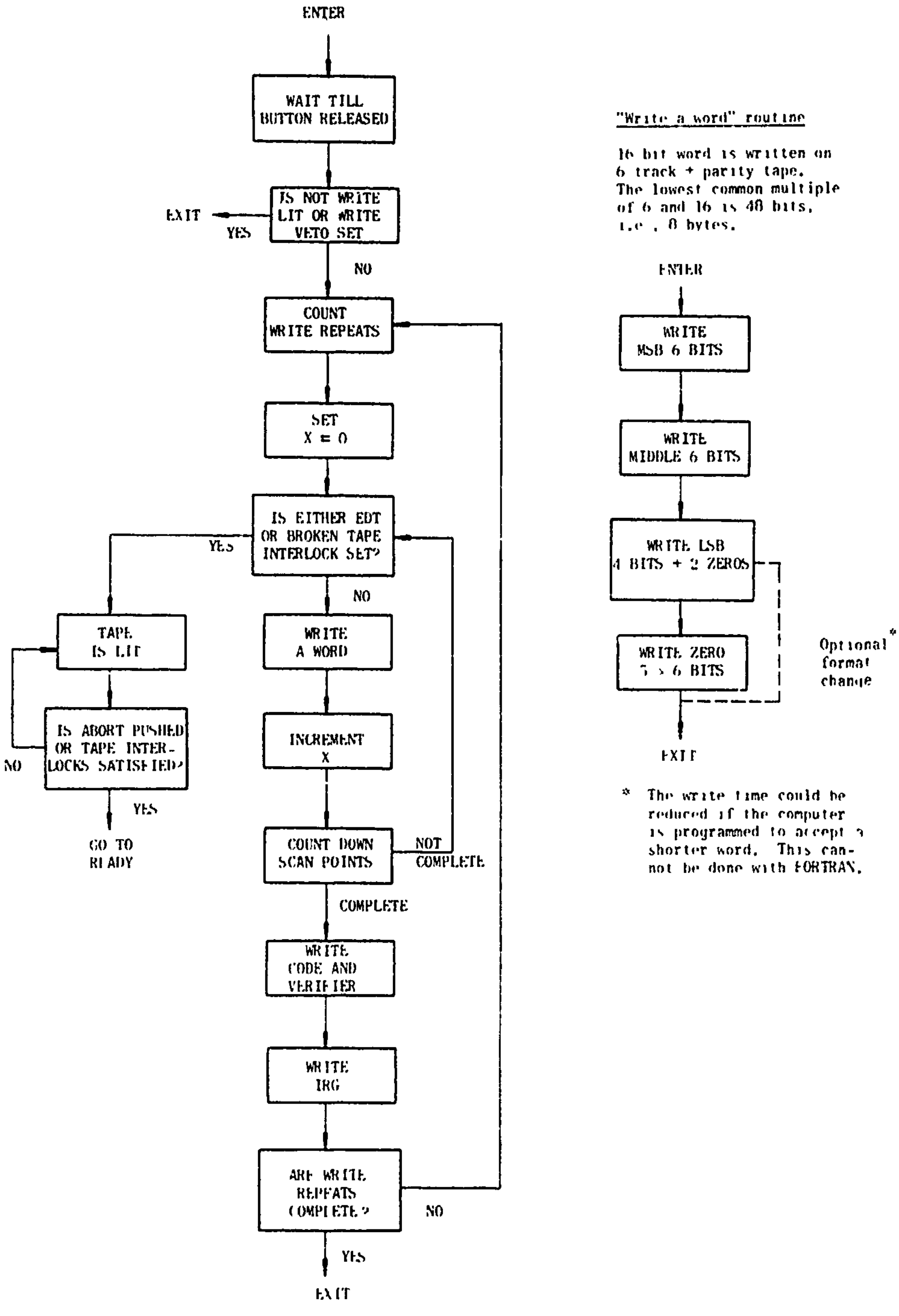


FIG. 31 Tape recorder WRITE routine.

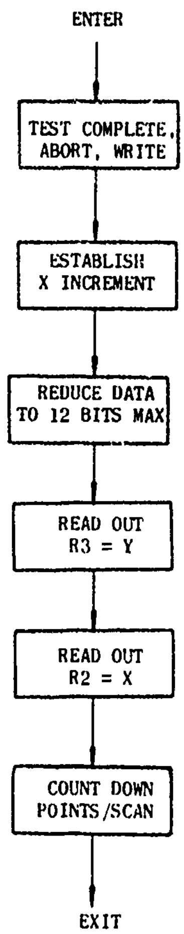


FIG. 32 DISPLAY routine.

SECTION 5

FORTRAN PROGRAM

The data card input for the FORTRAN program which processes the magnetic tapes has already been described in Section 2. The FORTRAN program consists of the main program LEE, together with several subroutines, viz.

(1) CPLEX, which implements several complex number operations,

(2) FTR, which performs fast Fourier transforms,

(3) PREP, which subtracts background waveforms, and prepares numbers for FTR,

(4) READIT, which reads data from magnetic tape; and

(5) MOVEF, which unscrambles each data word on tape for the READIT routine.

The main program LEE requires data cards which are read in as quantities NFOR and THIK. Nominally NFOR is the number of digitized samples taken in one scan, i.e., 64, 128, 256, 512, or 1024, and THIK is the sample thickness in mils, where 1 mil = 0.001 inch. Zero or negative values for these quantities have special significance. The program assumes the time interval between samples to be 9.77 psecs, the total width of the time window thus being 0.625, 1.25, 2.5, 5.0 or 10.0 nsecs, and the frequency interval thus 1.6, 0.8, 0.4, 0.2 or 0.1 GHz.

The program first reads in the quantity NFOR, halting if this is zero or negative. It then reads in each data record, or its duplicate if an error is detected, printing out each record in turn, and also printing out each reference and sample waveform with the appropriate background subtracted. It also reads in the sample thickness THIK card. Fourier transforms of the four input and output waveforms are taken, and these spectra are printed as a function of frequency. Finally these spectra are used to compute the S_{11} and S_{21} scattering coefficients of the sample, and from these μ^* and ϵ^* are computed using the procedure described in Section 2 of the Interim Report on this contract. Another THIK data input is read, permitting the following options:

(1)	THIK is positive:	Further records of sample data are read in, and μ^* and ϵ^* for the new sample computed.
(2)	THIK is negative:	The tape file is exhausted of data, and a new NFOR card is read to indicate whether a new file is to be read, or the program halted.
(3)	THIK is zero:	The next four records are replicas of the first four reference waveforms on the tape, and it prints out the <u>differences</u> at each sampled position on the four waveforms between the original data and the repeated version. Ideally these should be closely equal, variations indicating some changing parameter in the system, such as a loose connector or a changing pulse shape. Then a new NFOR card is read, to indicate if a new file is to be read, or the program halted.

Future variations of this program might include graph plotting routines for the waveforms, and for μ^* and ϵ^* . They might also include extra input parameters to inhibit unwanted printout of intermediate data.

SECTION 6

HIGH TEMPERATURE MEASUREMENTS

The controller program for high temperature measurements is identical to that for normal measurements given in Section 2, but with different apparatus. The sequence of operations is that given in Section 2.4. The high temperature measurements employ a different sample holder that is contained in an oven and capable of being cycled between room temperature equipment and 1000°F. A picture of the high temperature equipment is shown in Fig. 33, and a drawing of the sample holder in Fig. 34. The sample holder consists of a 1-3/4" split center section, similar to the room temperature holder, connected to two one-foot air lines, all parts being made from Kovar, with gold-plated conducting surfaces. The air lines have reduced wall thickness over most of their length to reduce heat loss. The sample holder is enclosed and supported in a quartz tube, the ends of which are covered with asbestos blocks. It is not essential that the quartz tube be used, and not to use it allows easier handling of the hot sample holder when samples are being changed. It has been the custom to circulate Argon in and around the hot sample holder, but this has not prevented oxidation of the KOVAR from air occluded in its surface. The gold plated surfaces inside the sample holder have remained in good condition. It is recommended that Argon should continue to be circulated internally at about 0.2 SCFM, particularly at the higher temperatures. Water cooling jackets for the sample holder outside the oven have been provided, but experience has shown that they are not needed below 1000°F, since heat conduction along the thin wall outer conductor is very small. The temperature of the oven is regulated by a Lindberg controller, and the temperature in the sample holder is monitored by a chromel-alumel thermocouple and a Leeds and Northrop potentiometer.

The method of installing a sample in the HI-TEMP SAMPLE HOLDER is illustrated in Fig. 35. The operator has the choice of employing either step (2) or step (3) to extract the inner conductor center link on which the sample is mounted.

(1) Unscrew the two knurled nuts and lift off the

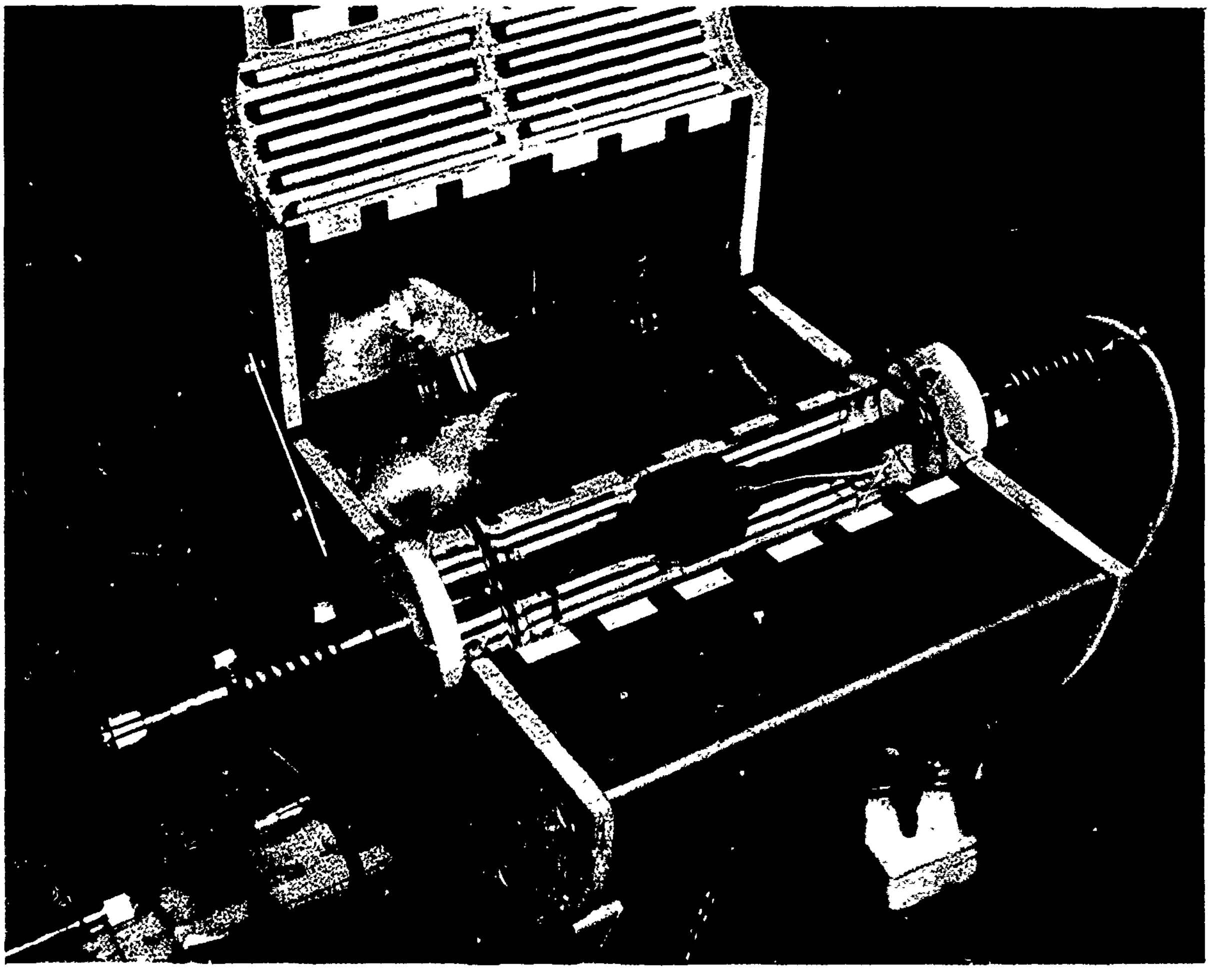


FIG. 33 High temperature sample holder inside quartz tube.

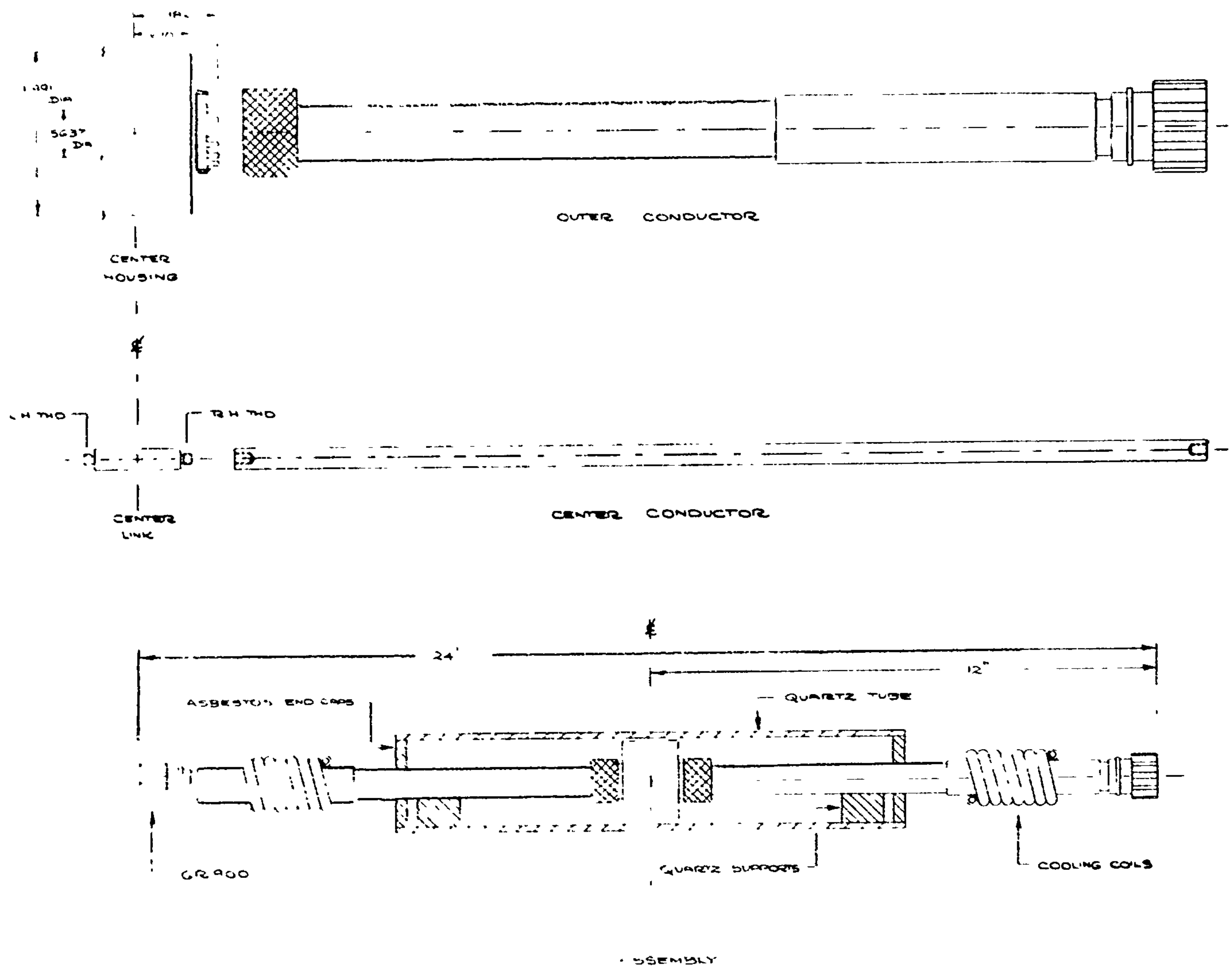


FIG. 34 High temperature sample holder.

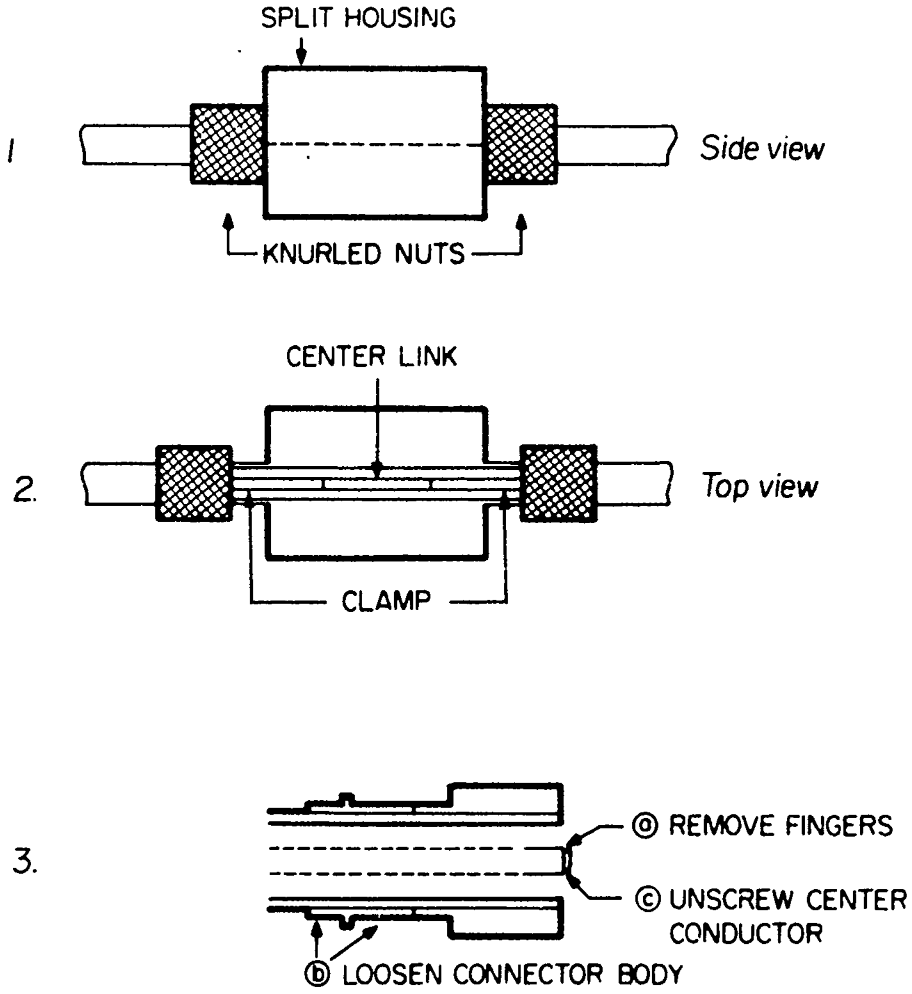


FIG. 35 Installation of sample in HI-TEMP SAMPLE HOLDER.

upper half of the split housing.

(2) The inner conductor is joined by a center link with counter-rotating threads on each end. The inner conductor should be clamped on each side of the center link and the center link turned until it can be removed. A pair of small clamps and a special pair of pliers have been provided for this purpose. The sample is placed over the center link which is then screwed back into place. There is a separate GAUGE BLOCK for the HI-TEMP SAMPLE HOLDER, which is used to set the distance between the outer face of the incident connector and the material used as a center conductor support (see Fig. 36).

(3) An alternative to step (2) is to dismantle one of the GR900 connectors at the end of the sample holder. A General Radio 900-TOK tool kit is required for this purpose. The sequence in dismantling the connector is:

   (a) Remove the spring fingers from the GR900 center conductor with the small Allen wrench.

   (b) Use both 11/16 inch wrenches to separate the body of the connector from the stainless steel ferrule.

   (c) Unscrew the center conductor with the torque handled Allen wrench.

   The connector may be re-assembled by reversing this procedure.

The HI-TEMP SAMPLE HOLDER is connected to the left hand part of the sampling head by the HI-TEMP CENTER LINE, and the HI-TEMP END LINE is connected to the far side of the sample holder. Care should be taken not to bend the CENTER LINE with a radius of less than 5", because there is a danger of distorting the geometry and causing an impedance mismatch. The end line is normally terminated in a short circuit, except for the "50Ω" measurement when it is replaced by a 50Ω termination.

The inner conductor of the HI-TEMP SAMPLE HOLDER is too long to remain centered unless it is supported. This presents a problem for the two COAX and the 50Ω reference measurements, since any support material then gives a mismatch. The best solution to this problem would be to change the

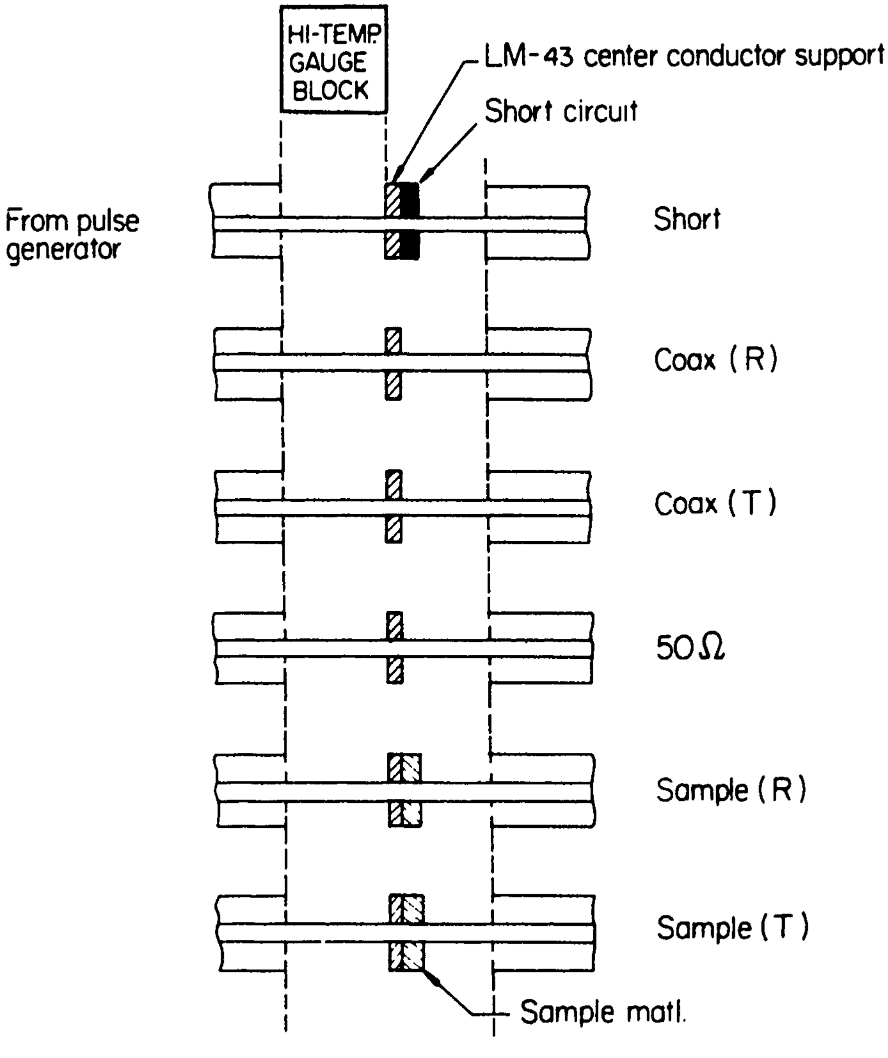


FIG. 36 Placement of material in HI-TEMP SAMPLE HOLDER.

dimensions of the inner or outer conductor at the location of the support to maintain the same characteristic impedance in the line. A satisfactory alternative is to include a thin, very low dielectric constant support material at the same position on the incident side for all measurements.

An .050 inch disc of LM-43* ceramic foam has successfully been used as support material for the center conductor. It has a dielectric constant of 1.5 and gives a relatively small perturbation to the line impedance. Material should be placed in the sample holder as illustrated in Fig. 36. The first order effects of the support material cancels out and very little error is introduced by the presence of the LM-43. Confirmation of this is provided by measurements made in the normal sample holder on a ferrite. The measurements were first made on the ferrite alone, and then the LM-43 was included for all measurements as in Fig. 36. No significant difference between the two measurements is apparent. A comparison of the results for the dielectric constant is presented in Fig. 37.

The HI-TEMP SAMPLE HOLDER has been made out of Kovar to minimize thermal expansion and the electrically conducting surfaces have been gold plated to reduce signal attenuation. Nevertheless, thermal expansion will contribute a timing shift to the waveform, which becomes a phase shift in the frequency domain. It is necessary therefore to make a set of reference measurements at every temperature that the sample is measured. It is more expedient in time to measure a full complement of samples at each temperature using the same reference waveforms, than to attempt to make measurements at many temperatures on a single sample.

*Emerson & Cumings, Inc., Canton, Mass.

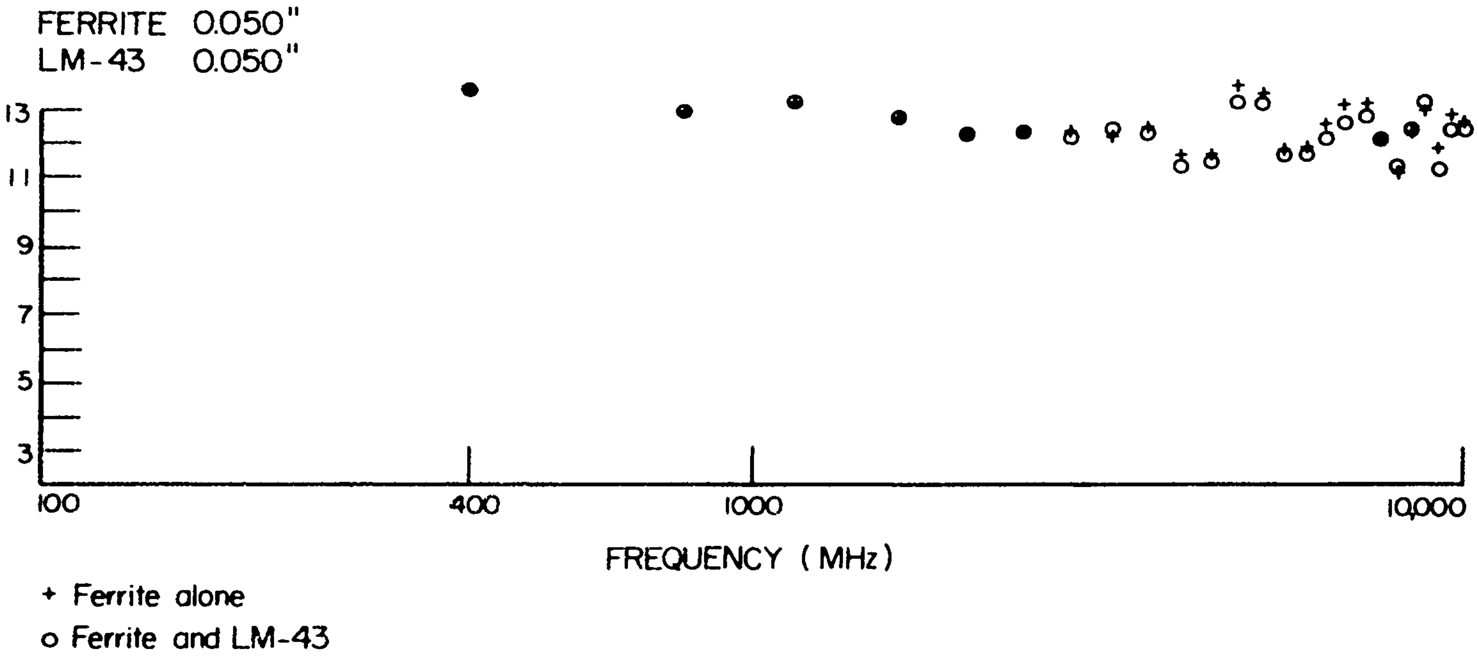


FIG. 37 Effect of LM-43 support on the data.

SECTION 7

MEASUREMENTS ON MATERIALS

During the course of the contract a variety of materials was supplied to SRRC for measurement on the 2.5 nsec time window system. The results of these measurements are included in this section as a series of graphs, with the exception of data on materials which were classified. The classified data on RAM materials has been supplied directly to the Contract Monitor, and is available on request.

The measurements were made as described in Section 5 of the Interim Report[1], and a list of the materials is given below:

Figure	Material
38	Nylon
39	Plexiglass
40	Epoxy
41	Wood
42	Alumina
43	Stycast Hl-K
44	ATCH Fiber board
45	PRD-49-1 Laminate (dry)
46	PRD-49-1 Laminate (dry)
47	PRD-49-1 Laminate (wet)
48	PRD-49-1 Laminate (wet)
49	LM-43 Ceramic foam
50	WC-8 Ceramic foam
51	F-1 Polyurethane foam
52	F-2 Polyurethane foam
53	F-3 Polyurethane foam
54	F-6 Polyurethane foam

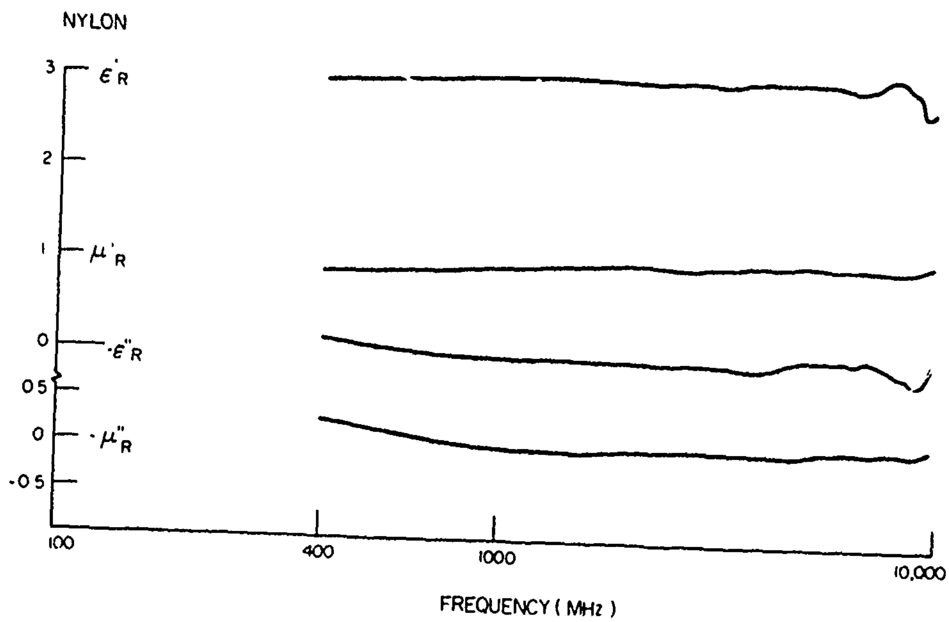


FIG. 38 Complex permittivity and permeability for Nylon.

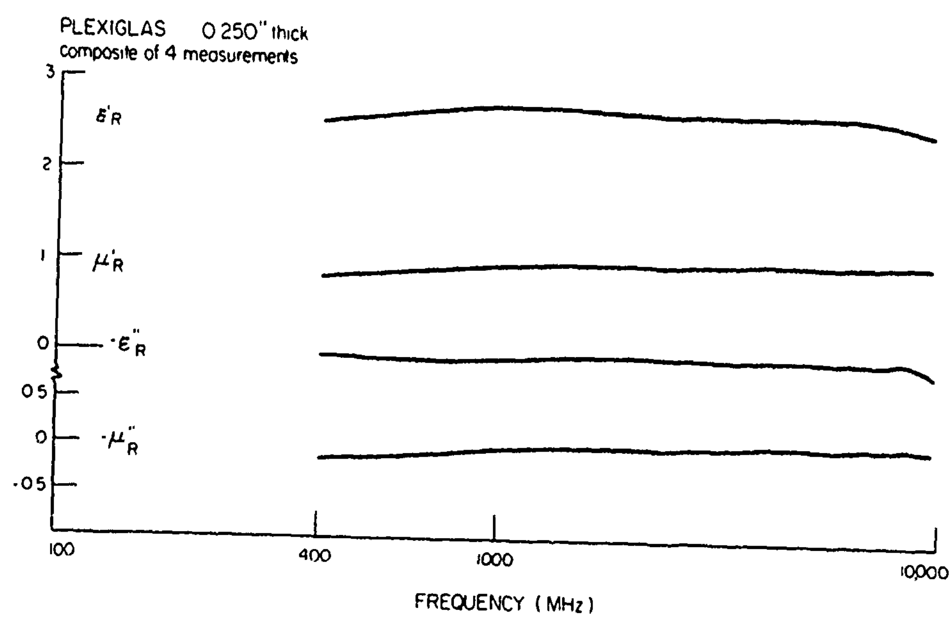


FIG. 39 Complex permittivity and permeability for Plexiglas

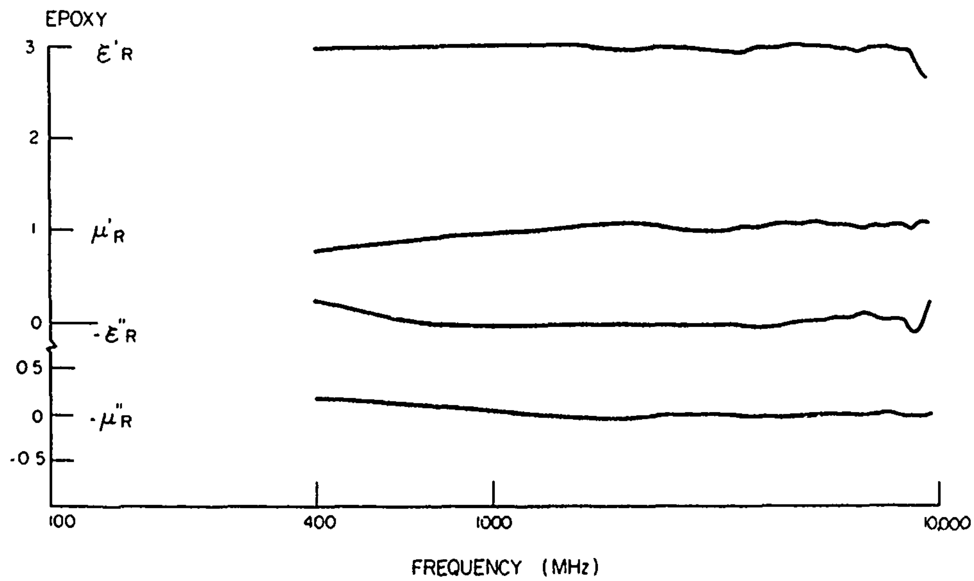


FIG. 40 Complex permittivity and permeability for Epoxy.

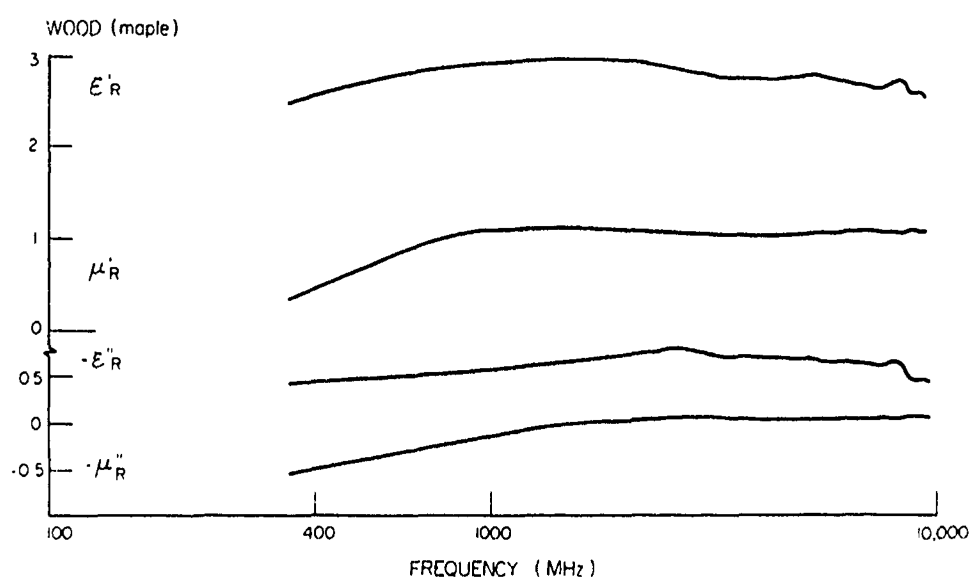


FIG. 41 Complex permittivity and permeability for Wood.

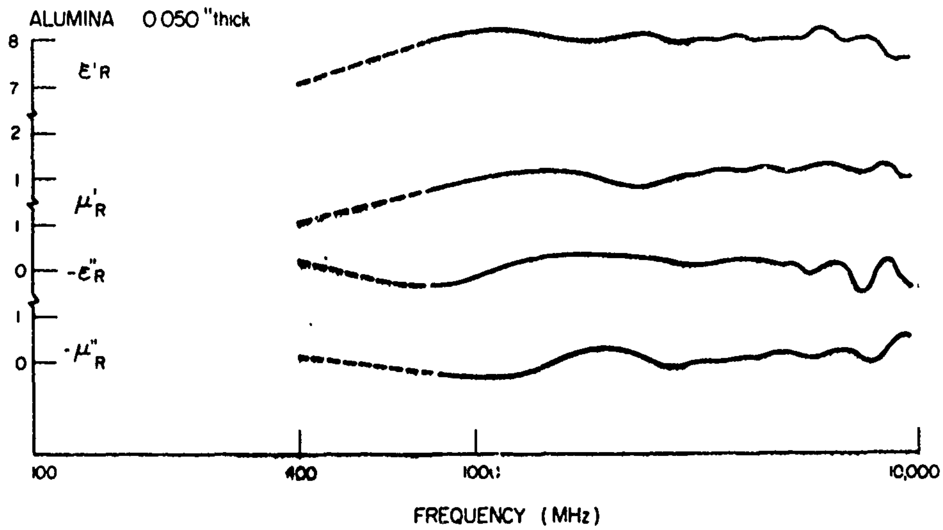


FIG. 42 Complex permittivity and permeability for Alumina.

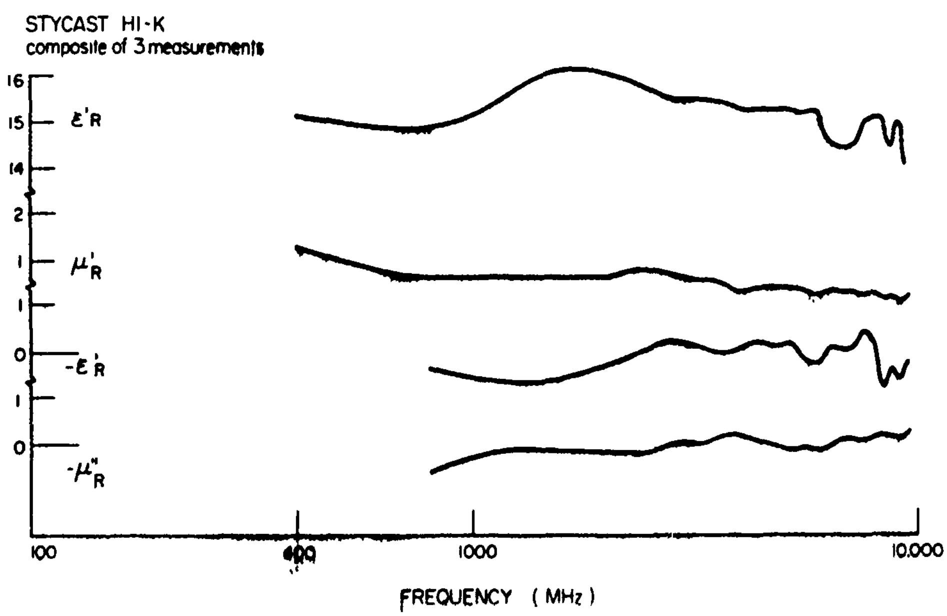


FIG. 43 Complex permittivity and permeability for Stycast Hl-K.

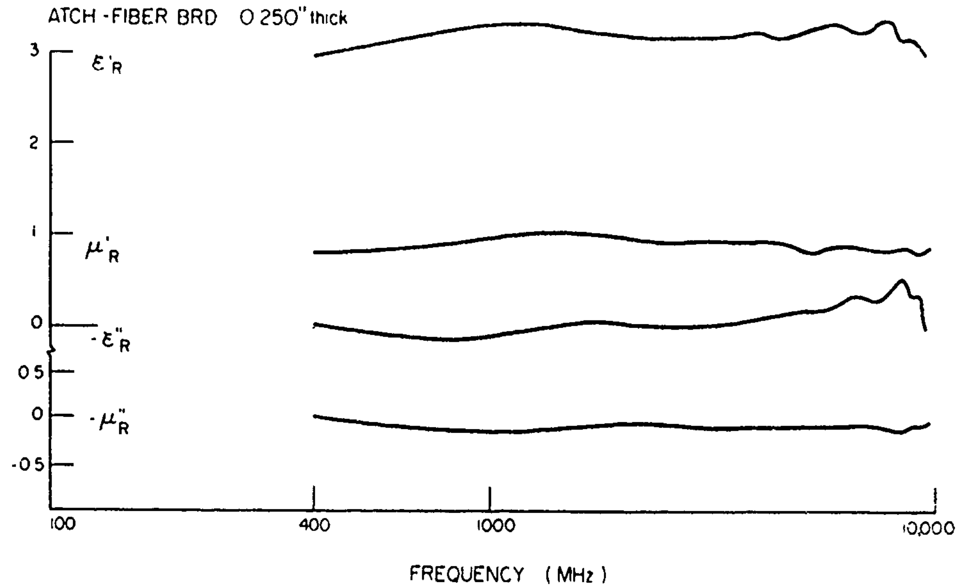


FIG. 44 Complex permittivity and permeability for ATCH Fiber board.

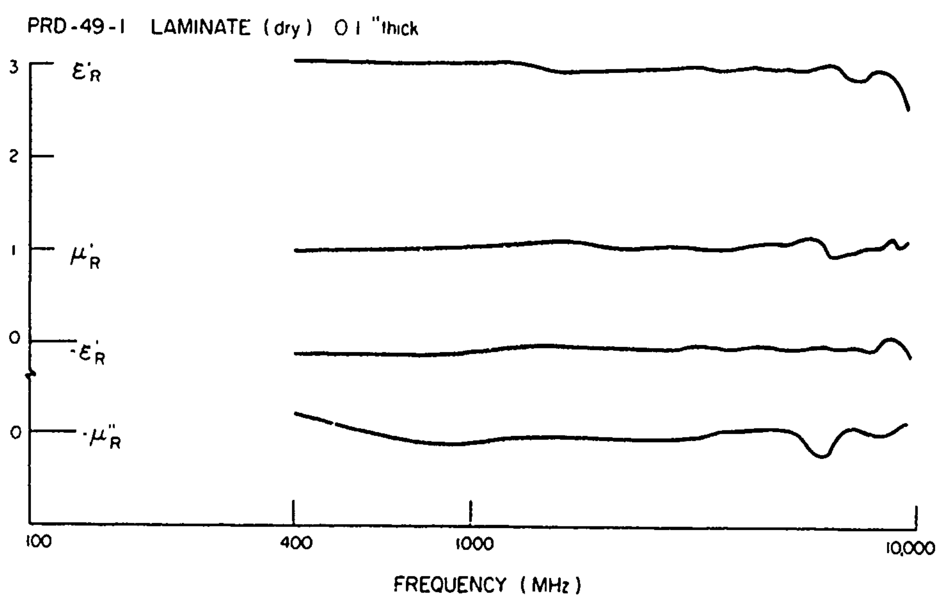


FIG. 45 Complex permittivity and permeability for PRD-49-1 Laminate (dry).

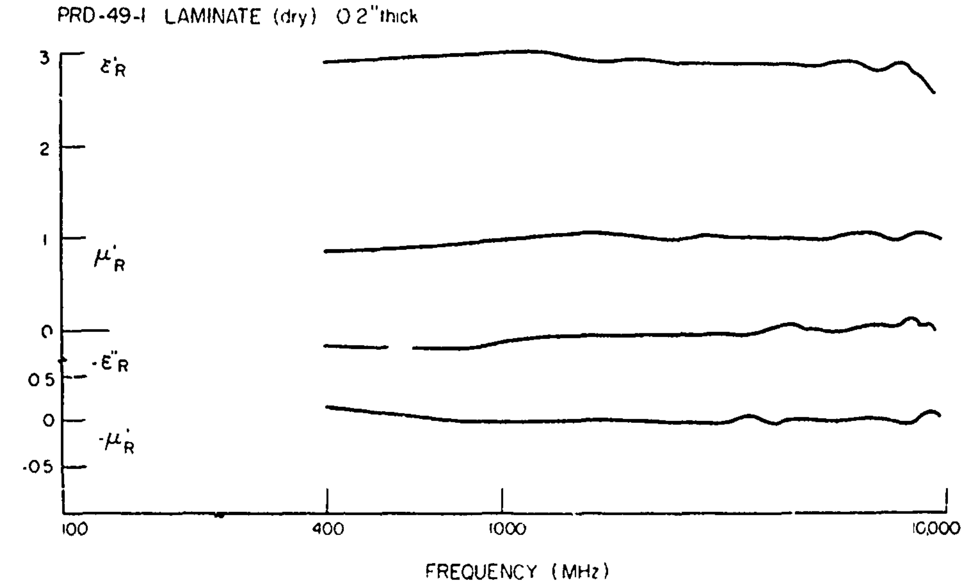


FIG. 46 Complex permittivity and permeability for PRD-49-1 Laminate (dry).

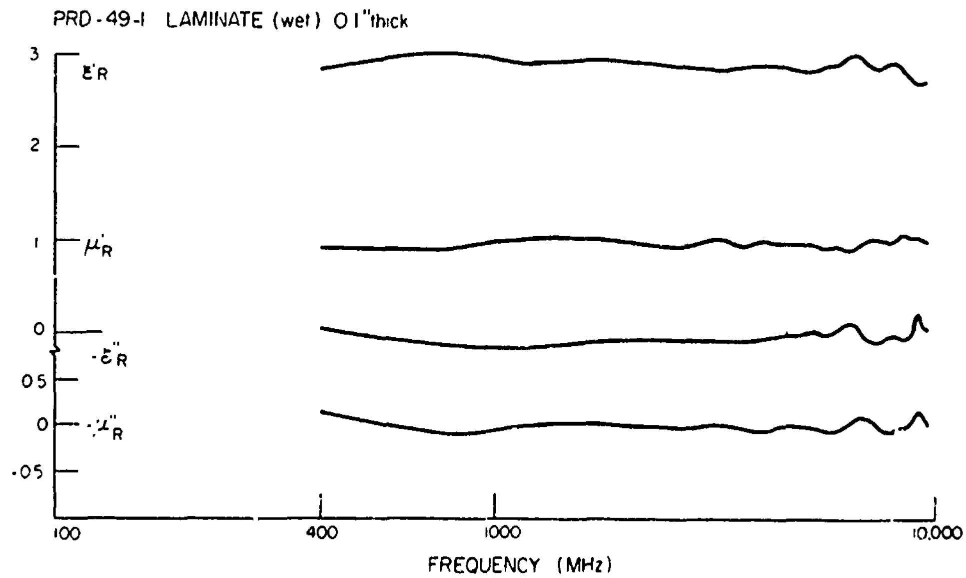


FIG. 47 Complex permittivity and permeability for PRD-49-1 Laminate (wet).

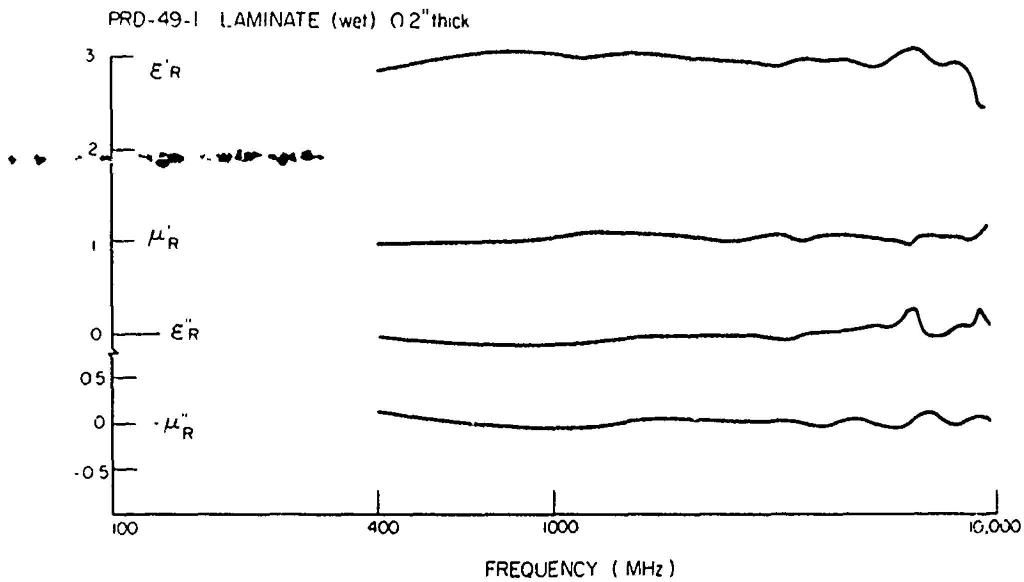


FIG. 48 Complex permittivity and permeability for PRD-49-1 Laminate (wet).

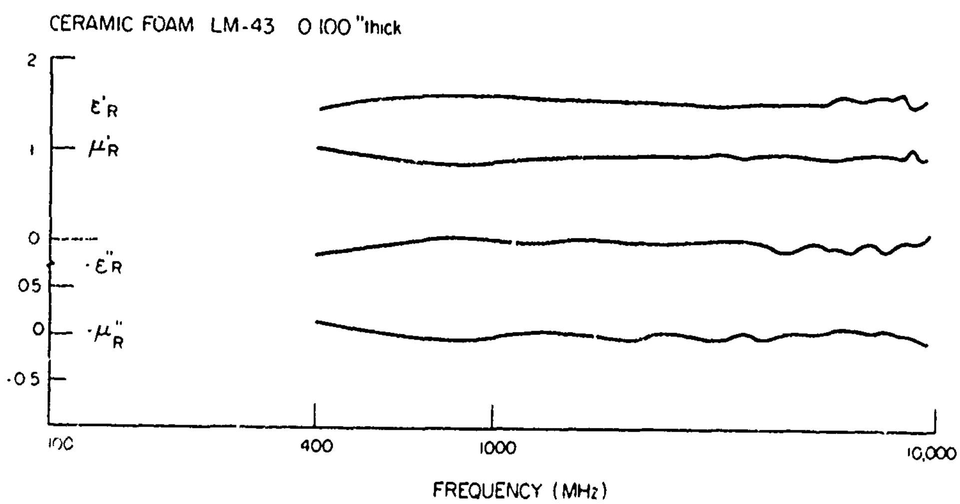


FIG. 49 Complex permittivity and permeability for LM-43 Ceramic foam.

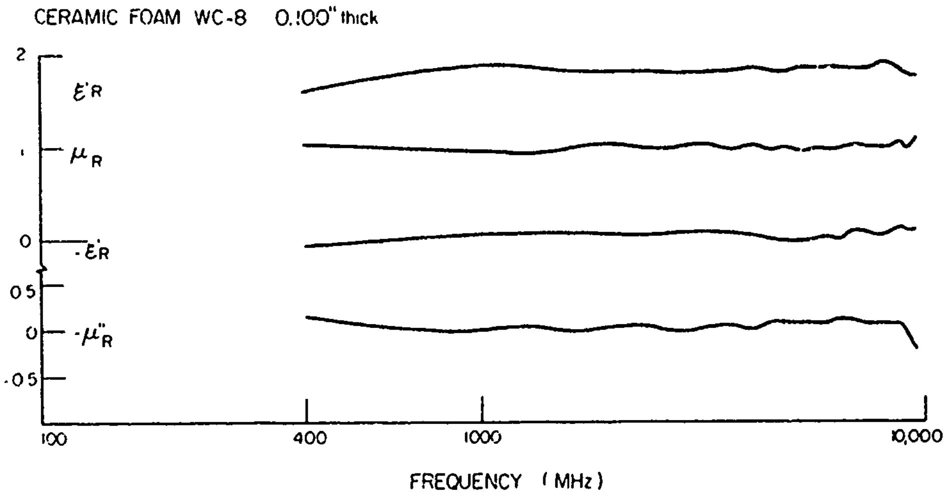


FIG. 50 Complex permittivity and permeability for WC-8 Ceramic foam.

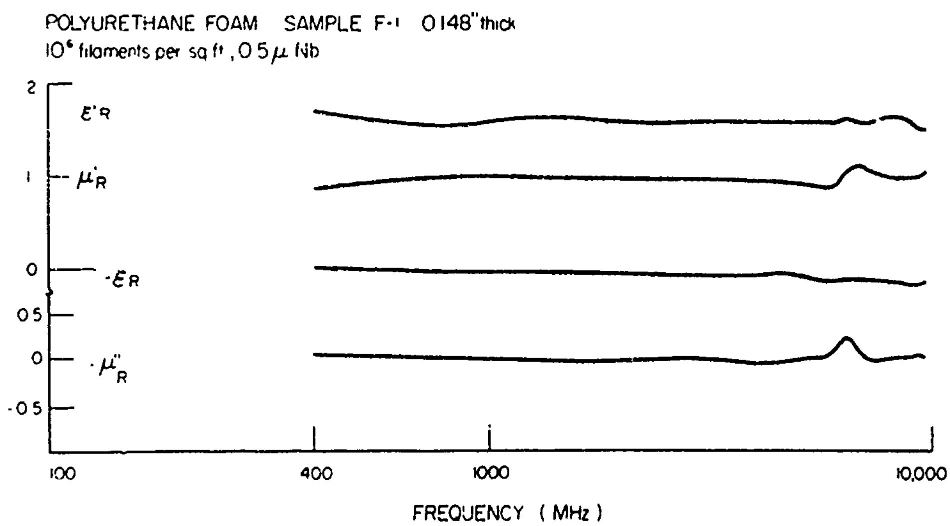


FIG. 51 Complex permittivity and permeability for F-1 Polyurethane foam.

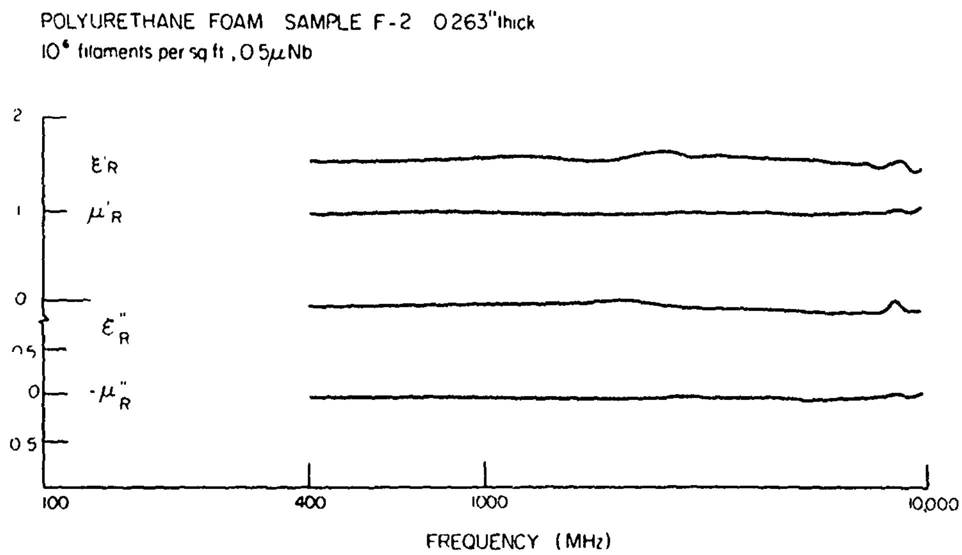


FIG. 52 Complex permittivity and permeability for F-2 Polyurethane foam.

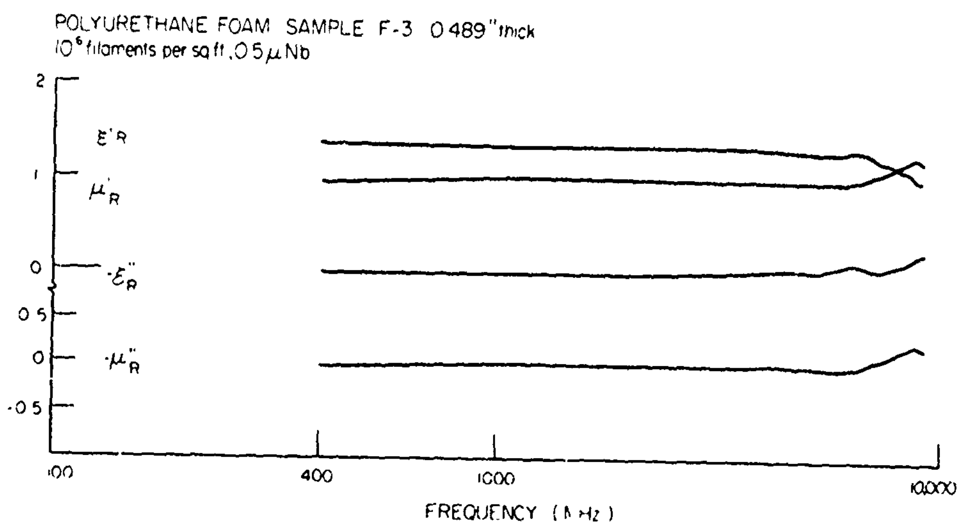


FIG. 53 Complex permittivity and permeability for F-3 Polyurethane foam.

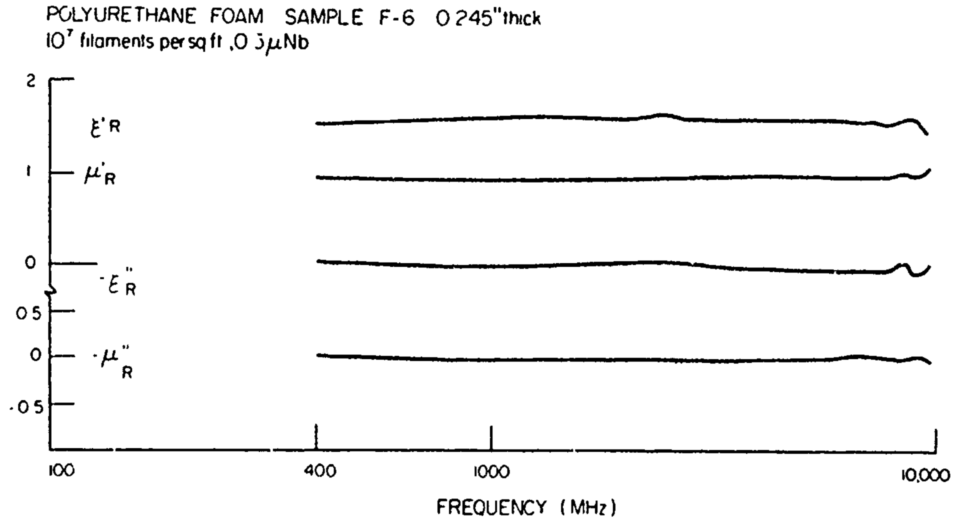


FIG. 54 Complex permittivity and permeability for F-6 Polyurethane foam.

SECTION 8

CONCLUSIONS AND RECOMMENDATIONS

The complete system described has been delivered and tested at the Air Force Avionics Laboratory, WPAFB. Several representative materials were measured over the frequency range 0.1 to 10 GHz, total measurement time for each material averaging 10 to 15 minutes. Comparison between the delivered 10 nsec system and the prototype 2.5 nsec window system at Sperry Rand Research Center gave the following conclusions:

(a) Noise levels were at least as low, and possibly lower on the new system, partially because of the compact structure of the equipment.

(b) Ripples due to connector and cable mismatches were larger in the delivered system, probably because of the necessity to use cable rather than precision air line when delays increased to 10 nsec from 2.5 nsec. The cables in question are those marked RG 331 to the right of the sampling head in Fig. 11. This effect is illustrated in Fig. 55, which shows 0.1 GHz resolution results from the new system, together with 0.4 GHz resolution results from the SRRC LINC system, for measurement of complex permittivity and permeability of Teflon. Both characteristics clearly show $\epsilon^* = 2.0 - j0.0$ and $\mu^* = 1.0 - j0.0$ over the range; but ripples amount to as much as ± 0.2 in the 10 nsec system, as against ± 0.1 in the SRRC 2.5 nsec system. This is not felt to be a serious limitation, since the solution is clearly to construct the longer air lines if the full 0.1 GHz resolution is necessary, or to duplicate the air lines of the SRRC system if 0.4 GHz resolution is acceptable. As seen on Fig. 11, the total delay in the RF331 cables is 15.9 nsec, and this could be replaced by about 15.6 feet of air line

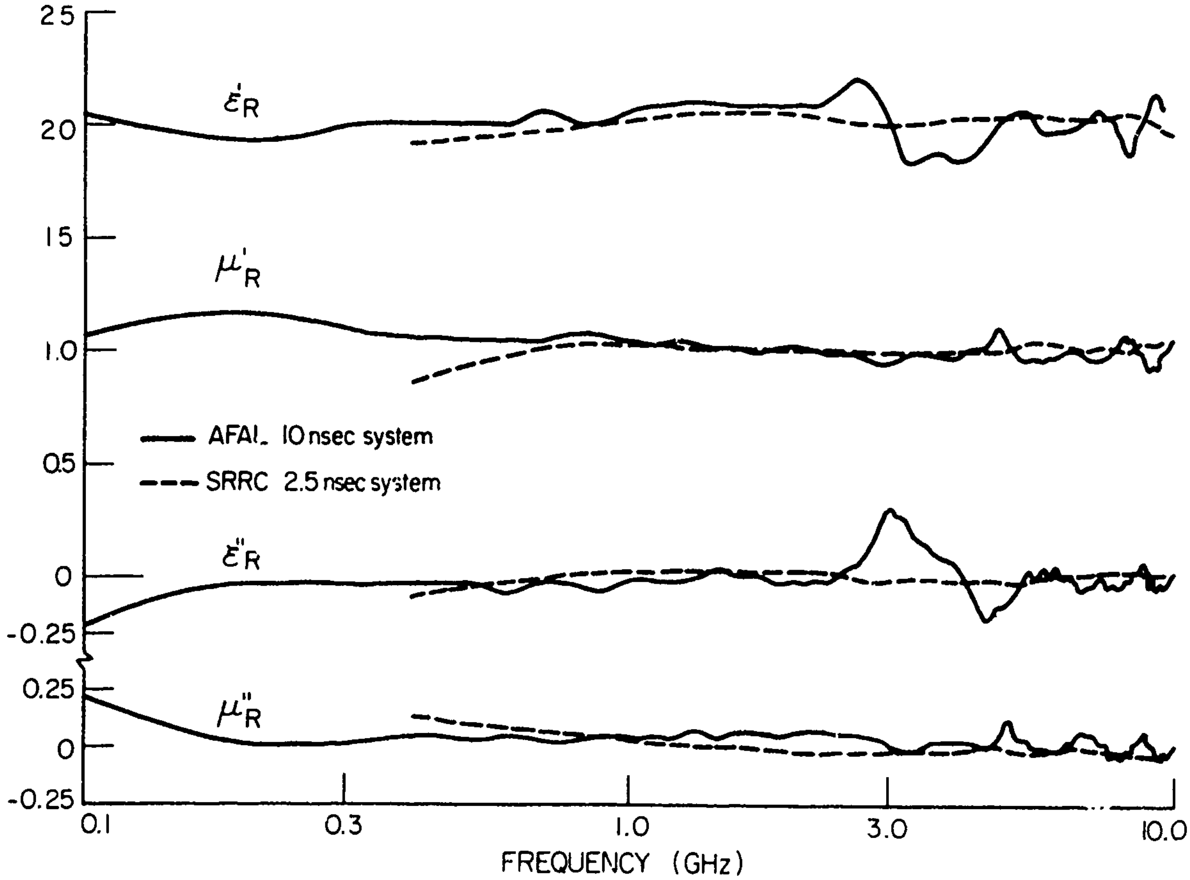


FIG. 55 Comparison of AFAL and SRRC results for Teflon sample.

In all other respects the system performs as expected, and provides a unique new tool to measure microwave materials. There are several new possible avenues of research to follow to explore its full potential, and because of the built-in flexibility allowed by the software program of the SPC-12, these would involve no changes to the basic system hardware, with the exception of new forms of sample holder. Among these we would list

(a) High temperature measurements. Work in this area revealed the problems involved, and the possible solutions. An alternative sample holder arrangement, based on the same split outer conductor principle, should allow convenient displacement of the oven assembly for changing samples, together with some method to cool the sample holder. The rapid measurement time of the system is at present offset by the 1-2 hours it takes for warm-up and temperature stabilizing. Care must be taken that the inner conductor of any rapidly heated sample holder is close to the temperature of the outer, to eliminate stress radially in the sample, and axially along the lines. Further work in this area has great potential, because of the difficulty of high temperature measurements on ferrite materials by any other frequency domain method.

(b) Low-loss materials. The system described in the Interim Report and in this report measures the real and imaginary parts of μ^* and ϵ^* with comparable accuracy, and thus is particularly applicable to high-loss RAM-type materials. For low-loss materials, tan δ measurements are inaccurate. A new form of sample holder for long (e.g., 1 foot), low-loss samples could be devised, with appropriate changes to the SPC-12 and Fortran programs for this new situation. Preliminary studies suggest that this technique might be useful down to about tan $\delta = 0.001$.

(c) Liquid dielectrics. Another form of sample holder could be devised, in which liquid is constrained by thin membranes across the coaxial line to form samples similar in dimensions to those

used at present. This could be used, for example, to study the changes in dielectric properties of casting resins as they set.

(d) Free space measurements. Frequently, materials to be measured are sufficiently inhomogeneous in 9/16" diam. samples that they must be measured as large slabs, presently by frequency domain interferometric techniques. Loaded plastic foams, for example, can have cells up to 0.1" diameter, and are too fragile and inhomogeneous to measure as small samples. Previous research has been made on time domain free space measurements,[2] the main problem being to find a satisfactory method to launch and receive impulsive waveforms. Since that time, parallel-plate horns have been developed for this purpose,[4,5] and transmission and reflection measurements from large planar samples may be feasible. Since reflected signals are small in amplitude, and hence a new, larger amplitude pulse generator would be required, the effort required in this area would be more substantial than the previous applications mentioned. Basically, however, the same instrumentation system would be directly applicable.

We have mentioned only materials measurements above, but time domain metrology research is continuing in applications to microwave networks analysis and to antennas and scattering. To all these areas, the time domain sampling, averaging, and recording system described in this report has immediate application.

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4. L. Susman, D. Lamensdorf, "Picosecond Pulse Antenna Techniques", Technical Report RADC-TR-70-20S, October 1970, Interim Report on Contract F30602-70-C-0088.

5. L. Susman, D. Lamensdorf, "Picosecond Pulse Antenna Techniques", Technical Report RADC-TR-71-64, May 1971, Final Report on Contract F30602-70-C-0088.

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13 ABSTRACT

This report describes a prototype time domain metrology system built under contract with the Air Force which could significantly reduce the time required to measure the properties of radar absorbing materials used on aircraft and missiles. During the development of such materials, many measurements are required of dielectric constant and permeability at different microwave frequencies, and by conventional means these can become very tedious. A system has been developed and delivered to the Air Force Avionics Laboratory, WPAFB, which generates subnanosecond risetime pulses, and measures the transient response of samples of the RAM material to these pulses. These time domain responses are measured and recorded on magnetic tape, and a subsequent Fourier transform program yields the desired ϵ^* and μ^* over the frequency range 0.1 GHz to 10 GHz. Actual measurement time averages only about 10 minutes per sample.

DD FORM 1473

Security Classification

14 KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Microwave absorbing materials						
Time domain						
Pulse generator						
Noise errors						
Timing shift						
Permeability						
Permittivity						

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